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ALL ABOUT SPACE Annual

Welcome to the very last **All About Space Annual**. While the final frontier will never cease to captivate and astound us, inspiring us to make great leaps in science and exploration, unfortunately, this is All About Space's last mission beyond Earth. To see us out, we've compiled some of the most fascinating recent stories from the pages of the magazine. So let's embark on our last expedition into space! Join us as we learn how the reality of climate change extends beyond our atmosphere and why we might very well have nine planets in our solar system after all. Delve into deep space for the final time to discover the secrets of Andromeda and explore the mysteries of white holes. Then, back down on Earth, we celebrate the greatest discoveries of all time and the groundbreaking women who have changed our understanding of the universe. Turn to page 110 and find out if you have what it takes to be an astronaut before donning your space suit and enjoy one last journey with us!

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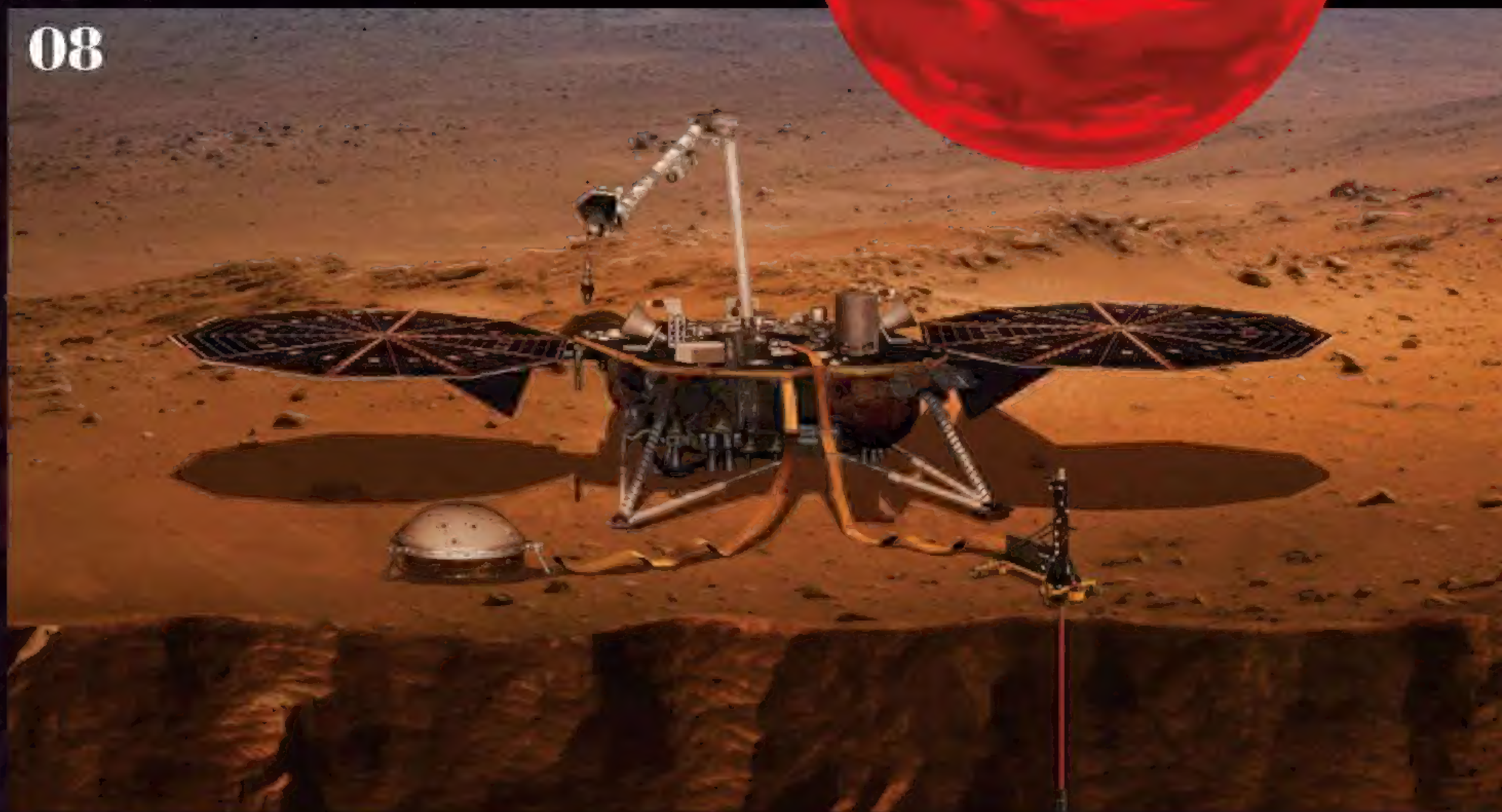
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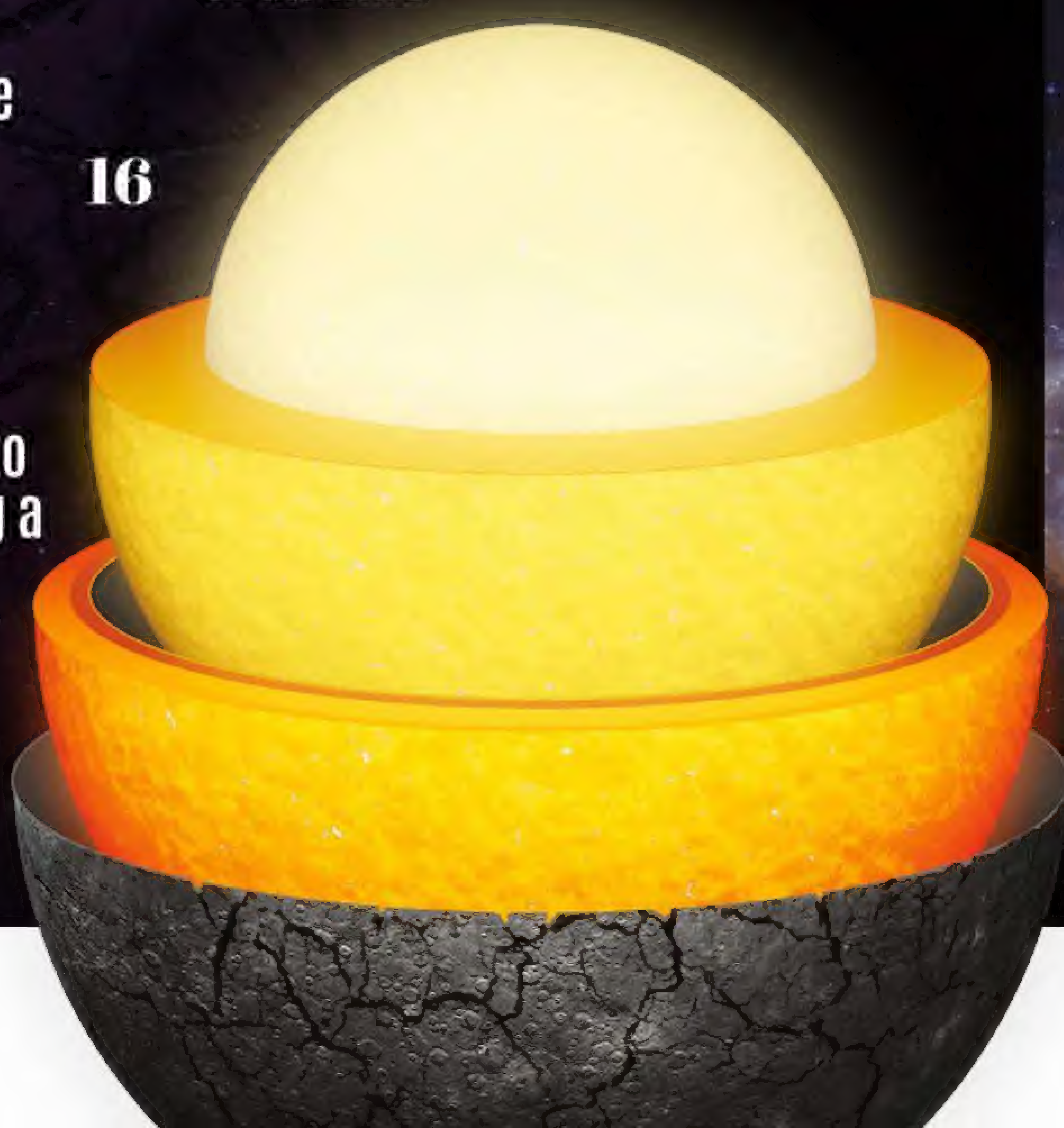
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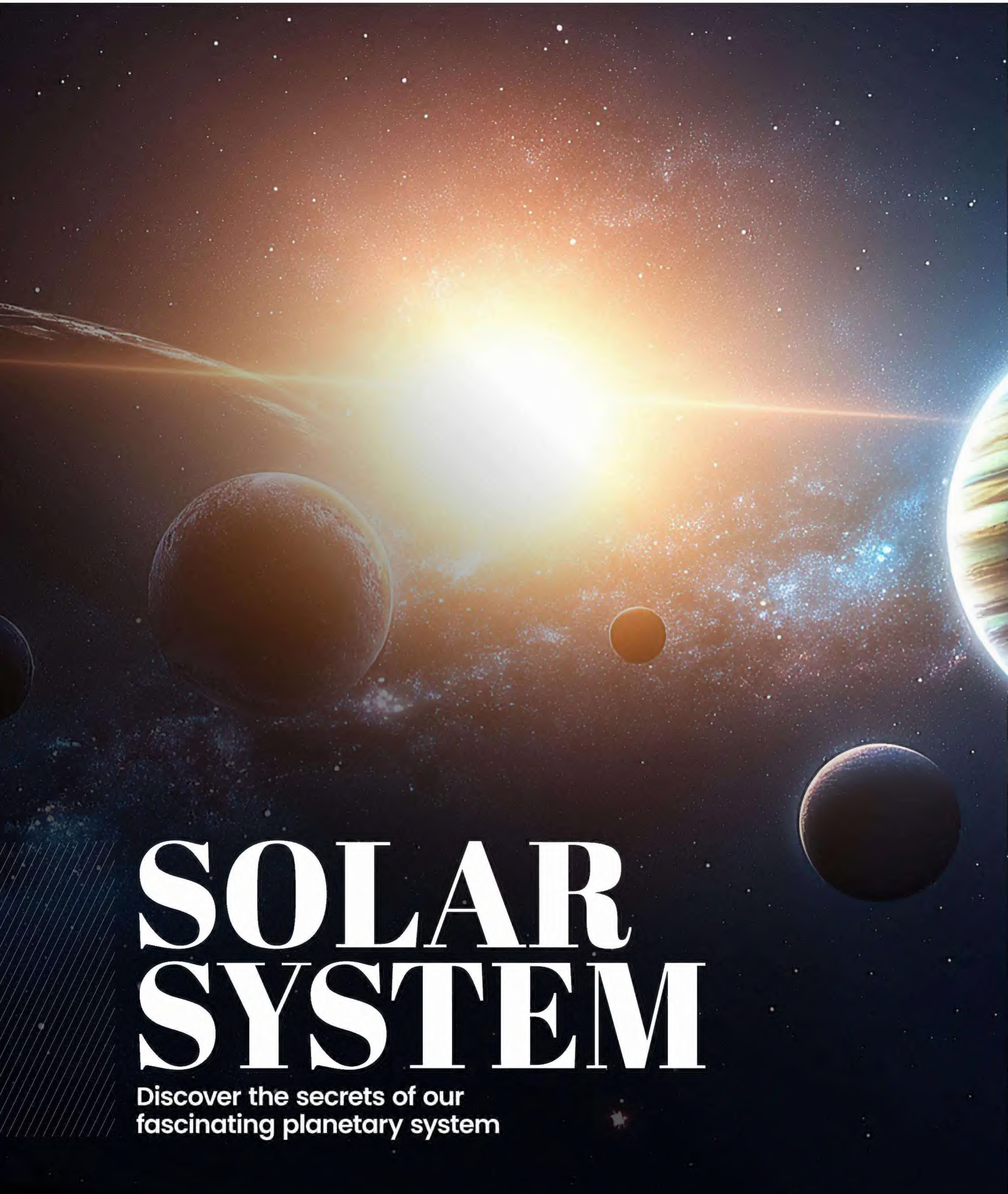

SOLAR SYSTEM

Discover the secrets of our fascinating planetary system


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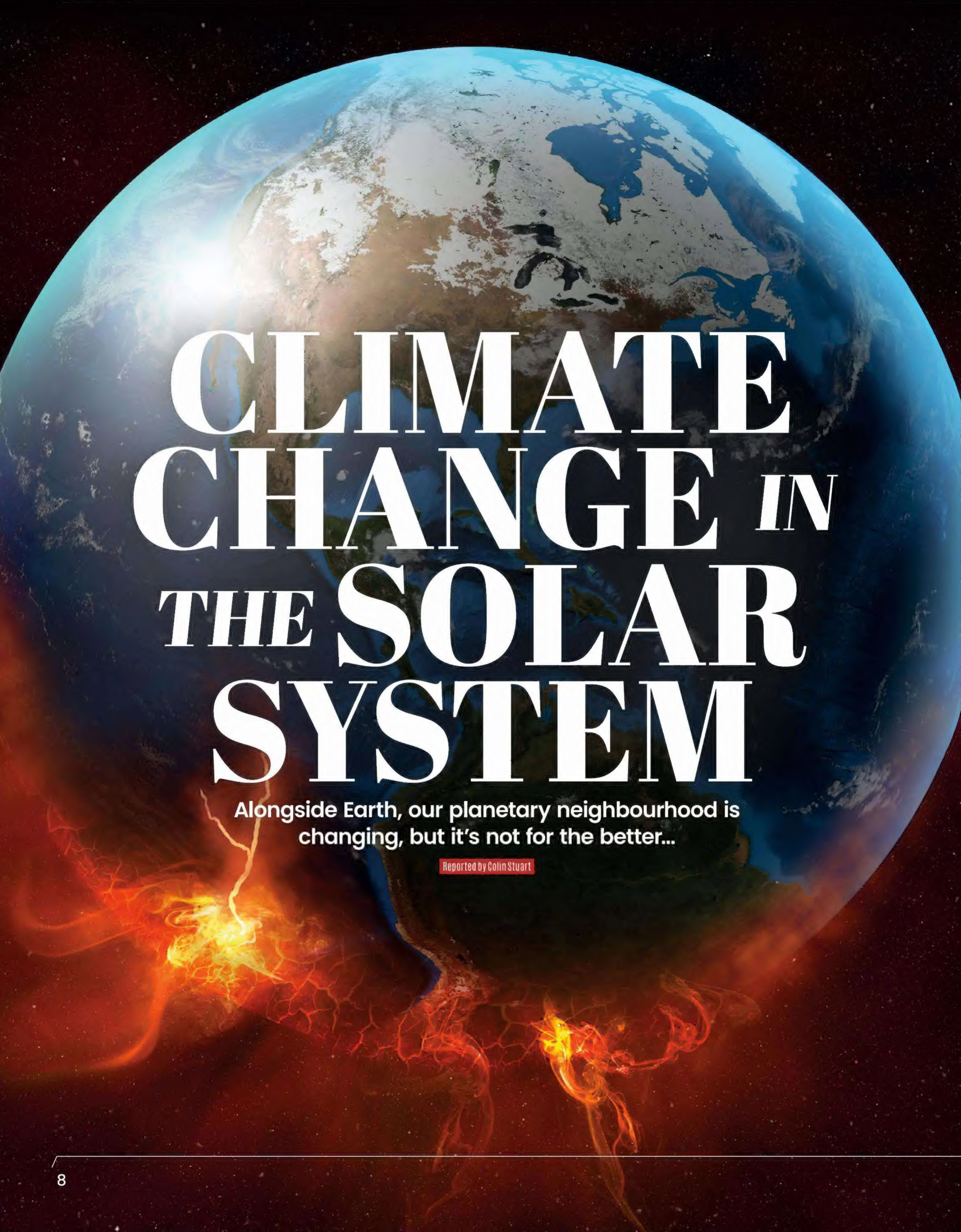


CLIMATE CHANGE IN THE SOLAR SYSTEM

Alongside Earth, our planetary neighbourhood is changing, but it's not for the better...

Reported by Colin Stuart

It's no secret that Earth is in trouble, and it's largely our fault. Since the Industrial Revolution we have been pumping so much carbon dioxide and other greenhouse gases into the atmosphere that our planet is rapidly warming. The race is on to keep the rise under 1.5 degrees Celsius (2.7 degrees Fahrenheit) over a 20-year average, it's a target we're predicted to miss. The consequences could be dire: rising sea levels, water shortages, increased migration and the possibility of more frequent wars as we battle each other for resources. Yet there is still time to turn things around. Public awareness of the issue has never been higher, and governments and individuals alike are slowly starting to wake up to their responsibilities – but will it all be too late?

Part of the trouble is that the climate of a planet is an incredibly complex system with a lot of moving parts. Throughout its history, Earth has warmed and cooled all on its own, alternating between ice ages and more temperate phases. How do we tease out our contribution from these ups and downs? According to Dr Nicholas Attree of the University of Stirling, we could do a lot worse than to look at our neighbours. "What we see on Earth is natural climate cycles, plus human influence," he says. "Looking at the cycles of other planets means we can better understand our cycles and better understand our influence."

Attree has been looking closely at Mars's past climate. It's the most explored planet in the Solar System, with a host of active rovers trawling the surface and satellites whizzing around it examining the ground from on high. We have discovered that, like Earth, Mars cycles through periods with different climatic conditions. The reason is simple: gravity. Unlike Earth, Mars has no large moon for stability. Combine that with the fact it is closer to Jupiter and Saturn and gets bullied by its giant neighbours. Being pulled this way and that leads to a change in Mars's obliquity – the tilt of the axis on which

The thick clouds on Venus prevent us seeing the surface in visible light

The HP³ probe on NASA's InSight measured Mars's internal heat

A regular cycle of ice ages

Earth's tilt changes over time, which leads to changing levels of solar energy hitting the planet. Ice coverage increases and the bright ice reflects more sunlight back into space, reducing the temperature even further.

VENUS BY NUMBERS

464°C
The average temperature in Celsius is around twice as hot as an oven

92
Atmospheric pressure compared to Earth; it's the same as being a kilometre (0.62 miles) underwater

0.69
Venus's albedo – it reflects 69 per cent of sunlight

96.5%
Venus's atmosphere is mostly carbon dioxide

243
Days for Venus to rotate, leading to a static climate

60
Winds move 60 times faster than Venus spins

600 million years
Venus's age when runaway greenhouse effects began

it rotates. It also changes the shape of Mars's orbit over time, making it successively more and less circular.

The upshot is that the intensity of sunlight falling on Mars is constantly changing, but in a regular way. A single cycle lasts tens of thousands of years. Attree has been looking at whether these climatic mood swings could have left a detectable signature on Mars today. "During warmer periods there would be an increased heat flow under the Martian surface," he says. "We've modelled how that heat would build up over time." Attree published a prediction that NASA's InSight may have been able to detect that excess heat. InSight landed on the Red Planet in 2018 and was equipped with a self-hammering 'mole' designed to burrow into the Martian dirt. Among its instruments was a thermometer – the Heat Flow and Physical Properties Package, or HP^3, perfect for looking at subsurface heat.

Unfortunately, the mission was beset with difficulties. On its first attempt the mole reached a depth of just 35 centimetres (13.8 inches) before getting stuck. Mission scientists tried to puzzle out the problem and see if it could get as deep as planned, but by their own admission it wasn't looking promising. Detecting Attree's predicted excess looked difficult. "We were only likely to find it if the instrument was functioning perfectly," he says. All was not lost, however. There's another way to keep track of Mars's past climate cycles: carbon dioxide.

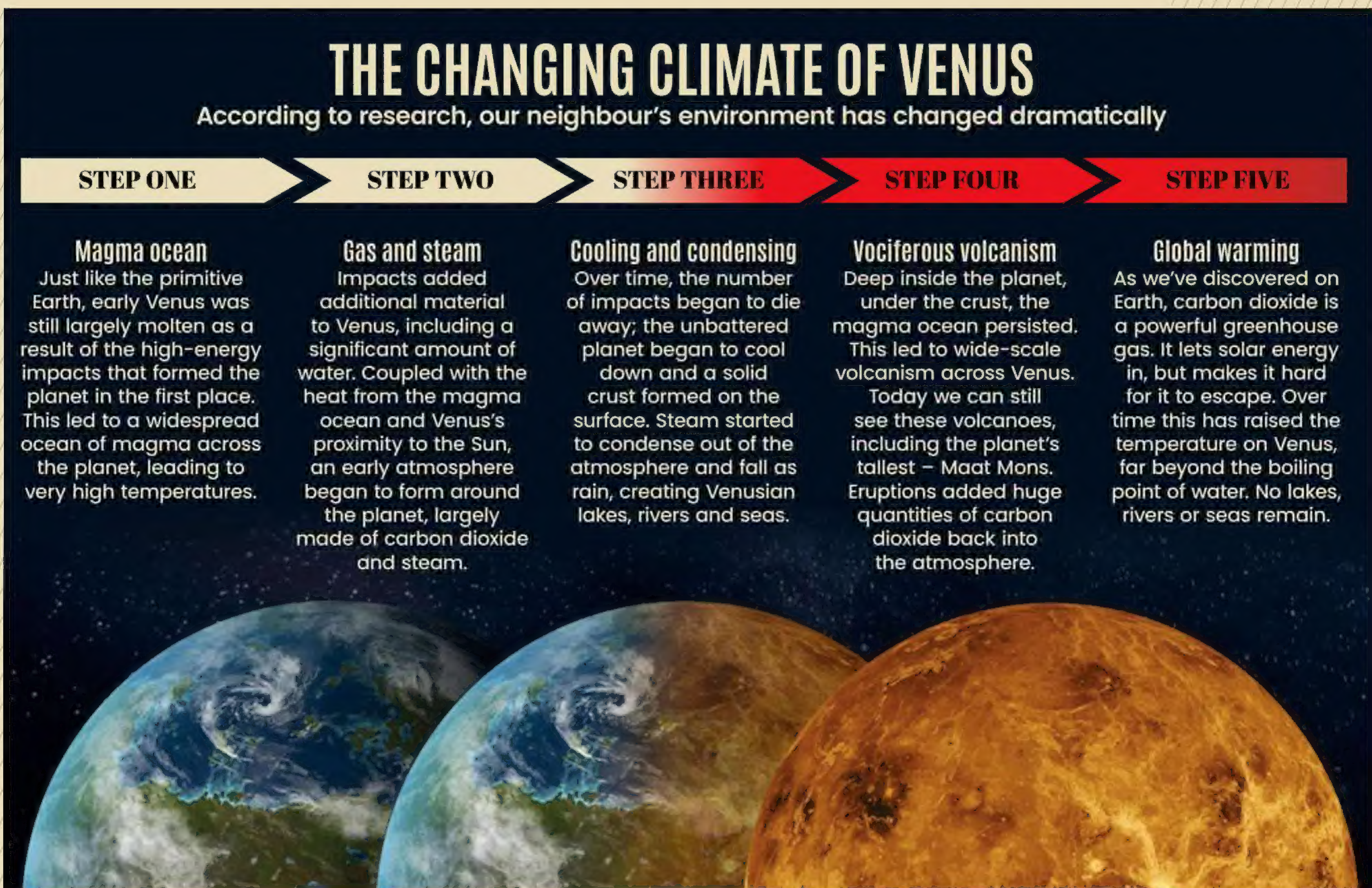
Today the gas that's causing us so many woes on Earth is the main constituent of the Martian atmosphere. Yet the air is so thin that the atmospheric pressure on Mars is just 0.6 per cent of Earth's. Carbon dioxide is also frozen into the Martian ice caps. When changes to Mars's orbit and tilt increase the Sun's intensity, the carbon dioxide ice sublimates – turns straight from a solid to a gas – and carbon dioxide is added to the Martian atmosphere. When things turn colder, the gas is deposited back onto the ice caps. In the 1960s it was predicted that the atmospheric pressure on Mars cycles in this way, getting as low as four times less than today's level and as high as double. Yet evidence to back this up remained elusive.

In December 2019, a study claimed to have found it at long last. It all hinged on the layers of carbon dioxide dry ice and water ice on the planet's south pole. A kilometre (0.62 miles) deep, it contains as much carbon dioxide as currently exists in the entire atmosphere. Radar measurements from orbiting satellites suggest the cap is formed of alternating layers of dry and water ice. Dry ice trapped under water ice shouldn't be stable, yet it seems to persist. Modelling by Peter Buhler of the Planetary Science Institute attempted to explain its longevity.

Each time Mars warms up, some of the dry ice remains trapped under the water

The impact of human industry

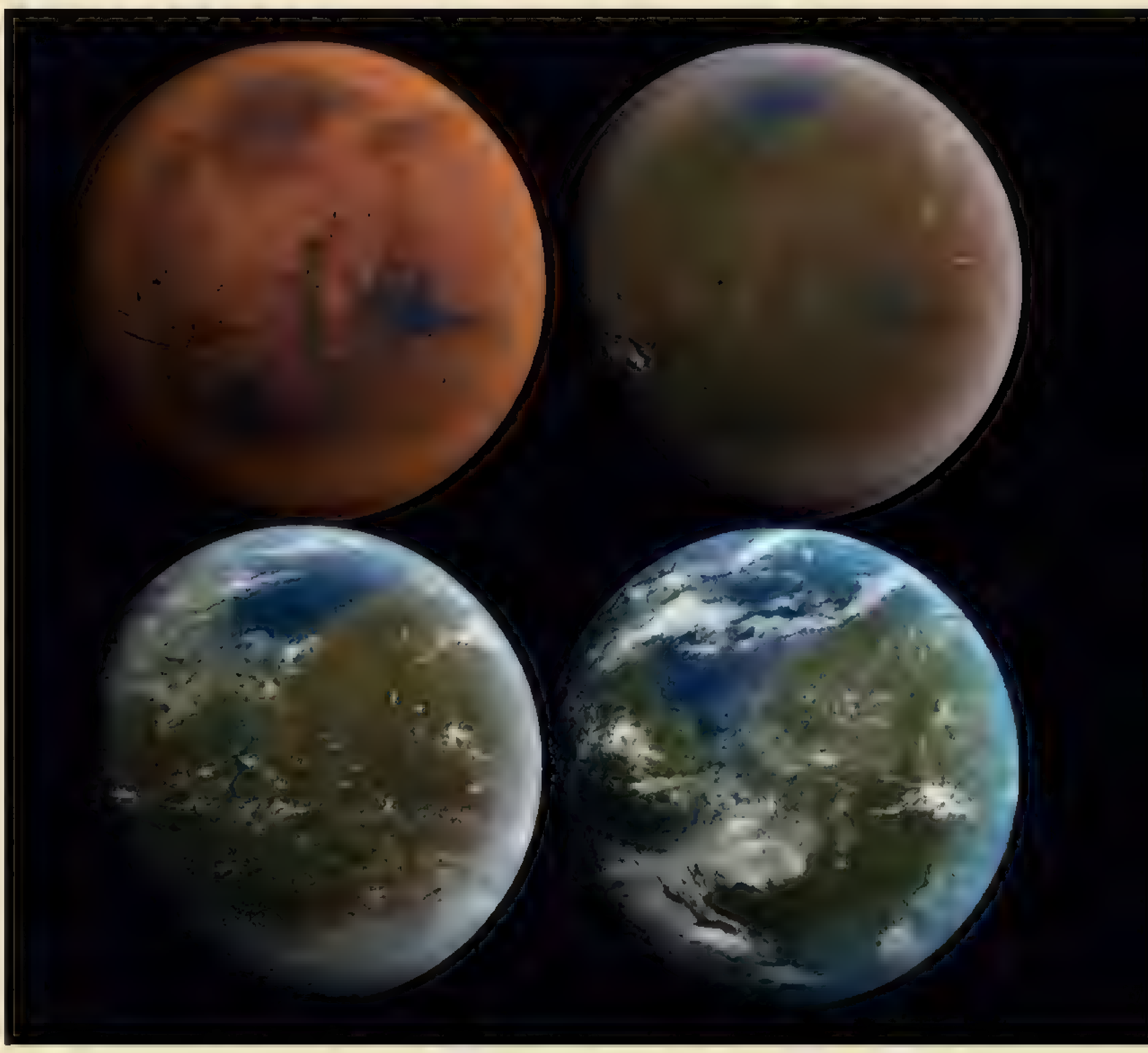
We've added carbon dioxide to the atmosphere, trapping more heat from the Sun. Our planet will adjust over time, but not soon enough to avoid severely impacting our way of life.



ice. The carbon dioxide that does escape is eventually deposited back on top of the water ice when the temperatures plummet. That leads to the layering we see. Studying these layers should allow researchers to more accurately construct a picture of Mars's climate stretching back billions of years to a time when the planet may have been habitable.

According to Michael Way from NASA's Goddard Institute for Space Studies, it could also help work out where to land when planning future human missions to the Red Planet. "They'd definitely want to talk to the climate modellers," he says. "It could tell you where to place your settlements or where the subsurface water is most likely to be." Way and his colleagues worked on adapting NASA's model of Earth's climate and applying it to other bodies in the Solar System, including Mars. It's known as a general circulation model. "It combines factors such as ocean circulation, wind circulation, cloud dynamics and different types of cloud," Way says. "It also estimates how many photons of light enter our atmosphere and are absorbed or reflected." Porting this model over to other worlds is not an easy task. "Applying it to modern Mars is very challenging," he says. It should get easier as improvements in computing power allow more intricate models to run in a shorter amount of time.

If Mars is hard, then modelling Venus's climate is even tougher. Thick clouds of carbon dioxide trap the Sun's heat, sending temperatures soaring beyond 400 degrees Celsius (752 degrees Fahrenheit). The atmospheric pressure is nearly 100 times greater than Earth's and over 15,000 times higher than on Mars. That has severely restricted our ability to land space missions on Venus. Those that did make it to the surface succumbed very quickly to the mayhem. "We have very few data points for Venus," says Way. Unlike Mars you can't just run rovers around, taking lots of temperature measurements. "Our models struggle as a result," he says.



A One day it may be possible to engineer Mars's climate to be more hospitable

V The European Space Agency's Huygens probe touched down on Saturn's largest moon in 2005

Models point to two different possible climatic histories for Venus, depending on how long the planet's early magma ocean hung around. The rocky planets formed when lumps of rock and metal called planetesimals smashed into one another with such ferocity that the solid materials melted. Being closer to the Sun, combined with the presence of a hot magma ocean, created an atmosphere of steam and carbon dioxide. "The atmospheric pressure would have been 1,000 times greater than the modern Earth," says Way.

A molecule of water is H_2O – two atoms of hydrogen bonded to one atom of oxygen. On a hot Venus, this bond would have been broken regularly. The hydrogen is lost to space and the oxygen becomes trapped inside the magma ocean. "If that's the case then Venus has been a dry, desiccated world for most of the last 4 billion years," says Way. The alternative is that the magma ocean was a much shorter phase. "Then it would have been cool enough to condense water into lakes, rivers and oceans," says Way – in other words, far more Earth-like than today. If it's the latter then Venus has experienced a huge change in climate over 4 billion years, largely thanks to the role of carbon dioxide.

Given our current climate predicament on Earth, is there anything we can learn from our neighbour? "It's a compelling idea," says Way, "but it's a difficult comparison to make." The driver of Venusian climate change is largely thought to have been large-scale volcanism dumping huge quantities of carbon dioxide into the atmosphere, far more than we've added to Earth's since the Industrial Revolution. "Unlike Venus,

CLIMATE CHANGE THROUGHOUT THE SOLAR SYSTEM

End temperature: where things turn extreme

4,700°C (8,500°F)

5,000°C
4,000°C
3,000°C
2,000°C
1,000°C
400°C
300°C
200°C
100°C
0°C
-100°C
-200°C
-300°C
-400°C

Mercury 167°C/332°F

There is evidence of pockets of water ice at Mercury's poles, especially at points that don't see sunlight, but these would soon evaporate.

Venus 464°C/867°F

Venus is already hellish, with a thick atmosphere that consists almost entirely of carbon dioxide. That would burn away if temperatures rose further.

Earth 15°C/59°F

The effects of climate change on Earth are already well-documented. Expect rising sea levels, a loss of sea ice, heat waves that are more intense and the altering of the seasons.

Moon -20°C/-4°F

The Moon's temperature rose by several degrees after astronauts paid it a visit – a change that wouldn't have much of an effect. Too much heat will break up the Moon's surface material.

Phobos -4°C/25°F

Mars -65°C/-85°F

The Red Planet has already seen climate change: a thinning atmosphere meant liquid water could no longer be stabilised on the surface. Under-surface water will eventually dry out.

Deimos -40°C/-40°F

Phobos

Phobos is less likely to be affected by climate change and more likely to find it comes to a sticky end by smashing into Mars.

Deimos

The smaller of Mars's two moons is slowly drifting away. It will eventually escape the Red Planet's gravity and find itself on a journey into space.

Ganymede
There is no atmosphere to trap heat on Ganymede, but it has its own magnetic field thanks to past heating that melted ice and caused rock to sink inwards.

Europa
The surface temperature of Europa is largely determined by its ability to retain the Sun's heat. Ice on its surface would be lost if the moon was heated.

We know that our Sun will become a red giant in approximately 5 billion years time. By then it will have consumed the terrestrial planets, though some planetary material will assimilate with this gas giant.

Titan
As its atmosphere has warmed in the past, pockets of liquid nitrogen may have exploded from the moon's crust. It suggests that Titan – which sees liquid methane fill those craters – may be susceptible to climate change.

Enceladus
Since it is mainly covered by fresh, clean ice, Enceladus will undoubtedly suffer should temperatures rise.

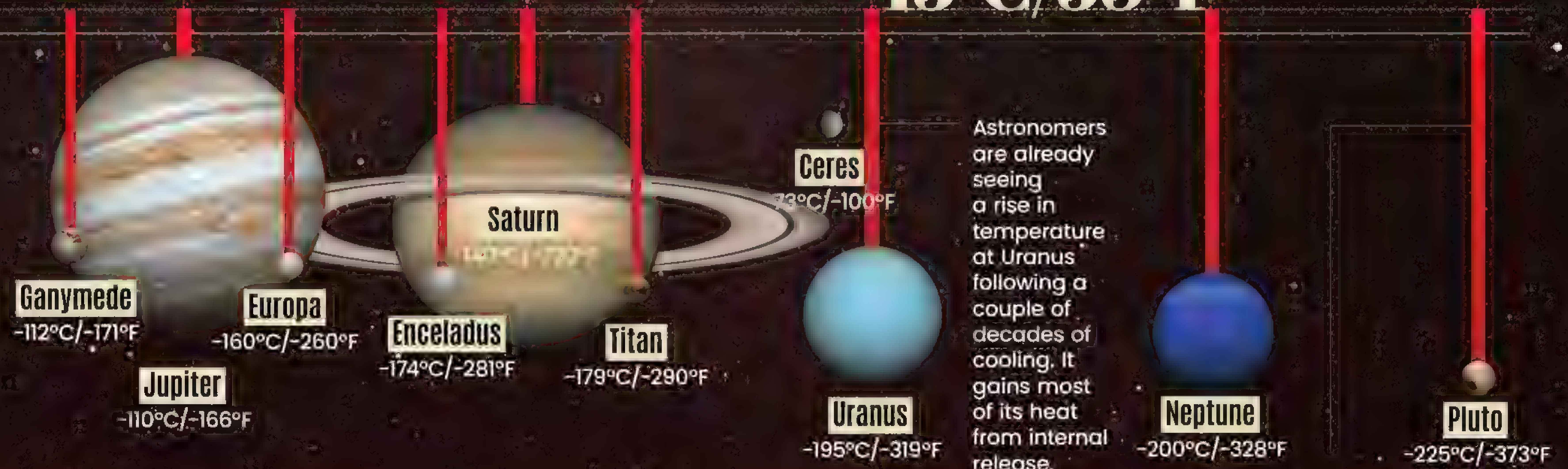
In the case of the Sun becoming larger and warmer, the rings of Saturn would end up being vaporised since they are made almost entirely of water ice.

Ceres
The dwarf planet Ceres is already talked of as potentially supporting life, and it is relatively warm and wet. Internal heat prevents it freezing up – a future home?

Neptune's atmosphere will boil off into space as it gets hotter.

Earth's average temperature

15°C/59°F



Astronomers are already seeing a rise in temperature at Uranus following a couple of decades of cooling. It gains most of its heat from internal release.

When Earth is burned to a crisp, Pluto will end up being in an odd situation of having average temperatures that mirror ours today. It will have a liquid-water surface as well as a thick atmosphere.

Earth will eventually adjust to this increase in carbon. We just may not be around to see it," Way says.

Way and his colleagues also secured funding to model the climate of Titan – the only moon in the Solar System with a thick atmosphere. "Titan is interesting as the density of its atmosphere is only 1.5 times Earth's," Way says. "A lot of its climate dynamics are similar too." Part of the attraction of studying Titan is the wealth of data that came back from the Cassini-Huygens mission. "What it found shocked a lot of us," says Way. Like Earth, there is liquid on the surface, which evaporates and condenses as rain. Yet instead of water it's methane, possibly because of the moon's very cold temperature. Researchers have also spotted complex chemicals known to be the building blocks of life. Understanding Titan's climate today could tell us whether it has ever had suitable conditions in the past for this chemistry to jump from prebiotic chains of molecules to full-blown organisms.

Dragonfly could be a potential game changer in this effort. In 2019, NASA announced that it had approved the audacious rotorcraft lander that would take off and land in several sites across the Saturnian satellite, much like its insect namesake. It's due for launch in 2028 and will arrive in 2034. According to Way, climate modellers are "eagerly awaiting its arrival". These efforts to understand the climates of the Solar System will do more than just inform our own battle against climate change. They will also give us a better idea of what exactly makes a planet habitable in the long term. If Venus was a pleasant planet before volcanism ran rampant, then perhaps we shouldn't rule out planets in similar positions to Venus around other stars. Maybe there is too much focus on the idea of a habitable zone – the narrow region around a star where the temperature is just right for liquid water.

The contents of a planet's atmosphere has a huge role to play in distributing heat, and surely needs to be taken into account when assessing a world's suitability for life. Who knows, one day we may have to evacuate this planet. If so, knowing which worlds around the Sun and beyond could be new potential homes could prove vital to the continuation of our species.

Colin Stuart
Astronomer and space science writer
Colin holds a degree in astrophysics, has written over 17 books on space and has an asteroid named in his honour.

© Getty

FOCUS ON

MARS LEAKS FASTER WHEN IT'S CLOSER TO THE SUN

The Red Planet has lost enough water to space to form a global ocean hundreds of kilometres deep

Seasonal changes can have a dramatic effect on how quickly Mars loses its water to space, a joint study between the Hubble Space Telescope and NASA's Mars Atmosphere and Volatile Evolution (MAVEN) mission has shown. Over 3 billion years ago, Mars was warm and wet, with large bodies of water on its surface and a thicker atmosphere. Today, however, Mars is desolate, cold and dry. So what happened to all the water?

Plenty of Mars's water is still on the Red Planet. Vast reservoirs appear to be locked up deep underground at depths between 11.5 and 20 kilometres (7.1 and 12.4 miles). There's enough water inside Mars for a global equivalent layer (GEL), which essentially refers to how deep a planet-wide ocean it would create, between one and two kilometres (0.62 and 1.24 miles). Relatively small amounts of water-ice are also locked up in shallow permafrost and in Mars's polar ice caps. During the Martian summer, this ice can sublimate, dumping water vapour into the atmosphere. Most of that water vapour circulates from pole to pole, freezing out in the hemisphere in which it's winter, but some finds itself in the upper atmosphere, where solar ultraviolet light can break water molecules apart into their component atoms. The oxygen in water ends up oxidising materials on the surface or bonding with carbon to form carbon dioxide. Meanwhile, the hydrogen atoms can escape into space and get carried away with the solar wind.

Based on MAVEN's previous observations, Mars has lost enough water to space to form a GEL tens to hundreds of metres deep. Combined with the huge amount of water found buried inside Mars, this implies the Red Planet was water-rich in its distant past. However, MAVEN, with the Hubble Space Telescope's help, has shown that the rate of hydrogen loss is seasonal, with large increases in the escape rate at perihelion, which is Mars's closest point in its orbit around the Sun. This coincides with a strong upwelling of water vapour into the middle atmosphere, caused by seasonal heating. When at perihelion, Mars's southern hemisphere is tilted towards the Sun and the Red Planet is engulfed in its annual dust storm season – the airborne dust can contribute to atmospheric heating and water vapour content.

"Scientists have found that Mars has an annual cycle that is much more dynamic than people expected 10 or 15 years ago," said John Clarke of the University of Boston. "The whole atmosphere is very turbulent, heating up and cooling down on short timescales, even down to hours. The atmosphere expands and contracts as the brightness of the Sun at Mars varies by 40 per cent over the course of a Martian year."

These Hubble Space Telescope images compare the thickness of the Red Planet's atmosphere and its water loss at perihelion to aphelion

MERCURY IS SHRINKING

The smallest planet in our Solar System is getting even smaller

Reported by Giles Sparrow

Mercury can be easy to overlook. As the closest planet to the Sun, it's hard to spot on its fleeting visits to our skies. Over the past few decades, however, our view of the innermost planet has been transformed by NASA's MESSENGER space probe. The first spacecraft to orbit Mercury revealed that this mysterious world has a complex history of its own, with a distant volcanic past, a core much larger than that of any other planet relative to its size and an active magnetic field. But perhaps most intriguing of all is the evidence that this tiny planet has shrunk considerably since it formed.

"Mercury is the least understood of our Solar System's four terrestrial worlds because until relatively recently it was extremely hard to image or visit," says Dr Paul Byrne of Washington University in St Louis. "It's deep in the Sun's gravity well, and we simply didn't know how to get a spacecraft into orbit around it until 1985." As a result of these challenges, most of our information about Mercury came from a single NASA probe that made three flybys of the planet in 1974 and 1975. Mariner 10 flew in a solar orbit that intercepted Mercury's, but the geometry of the two orbits meant that its encounters only revealed a little less than half of the planet's surface.

Despite the secrets of reaching Mercury's orbit being known from 1985, actually sending a spacecraft on the complex trajectory still presented considerable challenges, and it wasn't until 1998 that NASA seriously began to consider launching such a mission. Early proposals evolved into the ambitious MESSENGER mission, which launched from Cape Canaveral in 2004 and entered orbit around the scorching planet in March 2011 after a tortuous flight involving one flyby of Earth, two of Venus and three of Mercury itself. "I had the good fortune to be a member of the MESSENGER science team, so I've been with the mission pretty much from its early days," recalls Dr Tom Watters of the Smithsonian's Center for Earth and Planetary Studies. "We were in a happy position as the second spacecraft to visit Mercury and the first to actually orbit the planet, so in terms of pure discovery we were seeing parts of the planet that had never been seen before by a spacecraft."

Some of the most distinctive features on Mercury, known from the initial Mariner 10 flybys, were the elongated cliffs that weave their way across the cratered landscape. In places they cut craters in two, creating either a sharp height difference between one side of the crater and the other, or in some cases riding up across and completely burying part of the crater. "It was pretty obvious from Mariner 10 images that these fault scarps were widespread, and that suggested at least the parts of the planet that we could see had contracted," continues Watters. "It's like what happens to an apple when its core starts to dry out and shrink, and the skin starts to wrinkle and adjust to it. But we couldn't be sure the effect was global. When MESSENGER made its first flyby of the unimaged hemisphere in 2008, one of the first things that popped out was another of these very large scarps, which we now call Beagle Rupes. It was really after that we could confirm that we were looking at a global contraction of the planet."

So why exactly do these winding cliffs point to a shrinking planet? Byrne takes up the story: "These kinds of scarps are really not so uncommon, and you see them on Earth in tectonic settings. But the question was why are these

features so common on Mercury, which doesn't have separate plates? In order to answer this, you need a global shrinking process. If the volume of the planet is shrinking, then its surface area has to reduce as well to accommodate that shrinkage. What we're seeing in the lobate scarps is blocks that are being thrust up over their surroundings as the crust shrinks." Predictions that Mercury has shrunk over time go back to before the Mariner mission, and shrinking is an inevitable part of any rocky planet's history.

The collision processes that form rocky planets inevitably leave them with a molten interior – conditions in which heavy metals like iron and nickel sink into the centre to form a hot core, while lighter elements such as silica and oxygen remain closer to the surface, combining in silicate minerals to form a rocky mantle. Surrounded by the cold of interplanetary space, such hot planets must inevitably cool down over time. This cooling of planetary interiors inevitably leads to a reduction in the amount of space they take up. The other rocky planets have hidden much of the evidence of their own shrinkage through other geological activity, but on Mercury it remains for all to see, written in the starkly beautiful cliffs of the lobate scarps.

Adding to this is another mysterious aspect of Mercury – its giant metallic core. Discovered from density measurements taken during the Mariner 10 flybys, Mercury's core is about 3,600 kilometres (2,237 miles) across, surrounded by a thin mantle and crust that together are only about 420 kilometres (261 miles) deep. "Mercury's outsized core and thin mantle mean that it radiated heat more quickly," says Byrne. "Its contraction started sooner and lasted longer. The crux of the issue is just how much the planet has contracted."

Armed with MESSENGER data that includes a photographic survey of the planet from different angles and laser altimetry data to reveal the height of different structures, that might sound like a relatively simple question to answer, at least in principle. But it's here that Byrne and Watters come to starkly different

INSIDE A SHRINKING WORLD

Mercury's interior is dominated by a huge iron core that accounts for approximately 80 per cent of the planet's diameter and around 55 per cent of its volume

1 Solidifying inner core

Mercury's core is richer in iron than those of other terrestrial planets. The innermost core may have frozen into a solid ball of iron, with some other heavy elements present.

2 Swirling outer core

As Mercury's outer core of molten iron churns and swirls, it carries electrical currents that generate a magnetic field around the planet, which has about one per cent the strength of Earth's.

3 Iron sulphide layer

MESSENGER showed that Mercury's mantle is surprisingly dense. In 2012, NASA scientists proposed that the lower mantle is composed of dense iron sulphide that has risen out of the core and solidified.

4 Upper silicate mantle

The upper part of Mercury's mantle is composed of silicate rocks with very little iron. Such a thin layer contains few radioactive minerals to help keep the planet's interior hot.

5 Thin crust

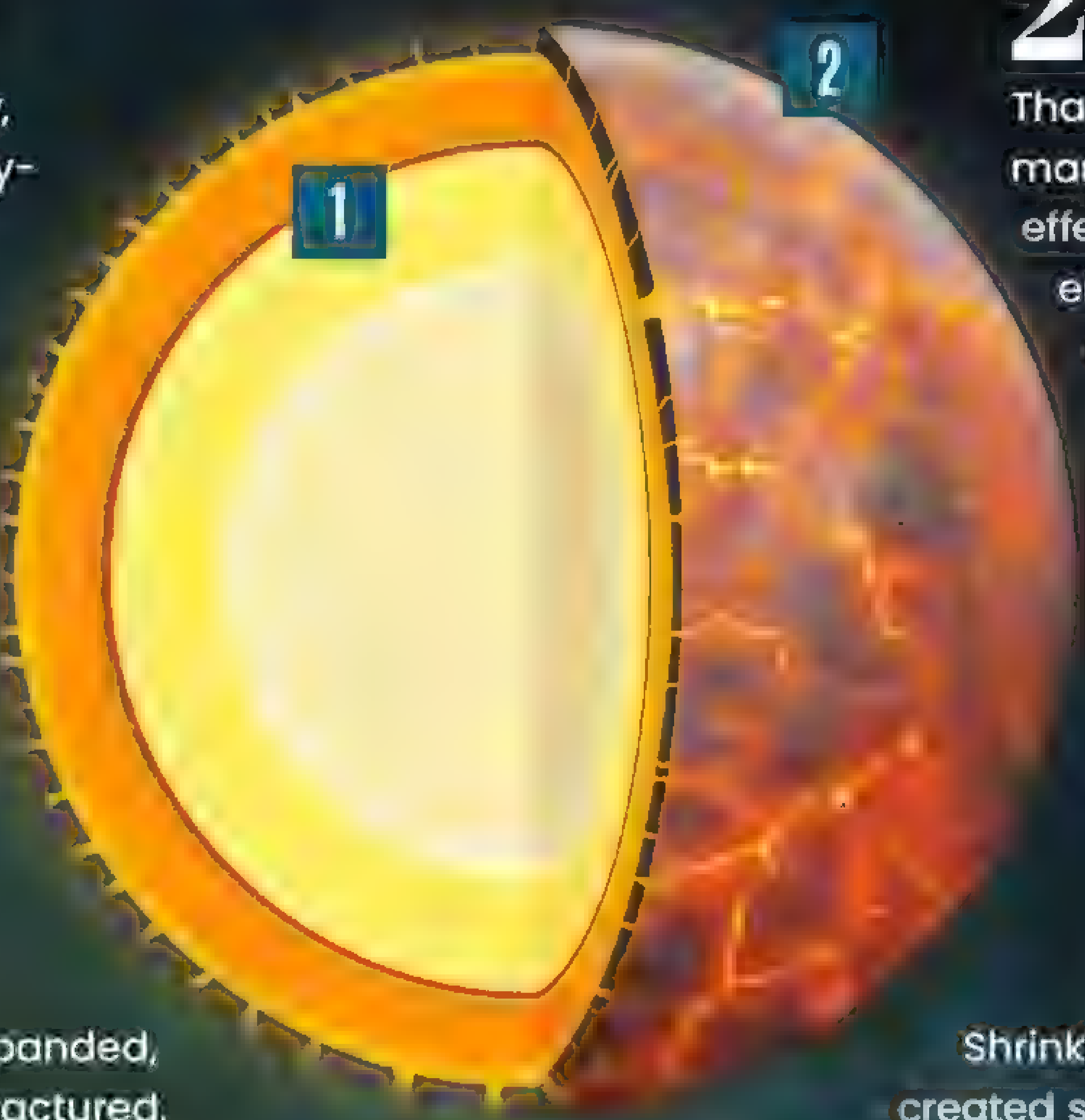
Mercury's solid crust forms a thin layer on top of the mantle. It was shaped by volcanic activity early in the planet's history, by compression and faulting as the interior contracted and also by bombardment from space rocks.

HOW MERCURY IS GETTING SMALLER

Changes to its internal temperature and loss of heat into space have caused the little planet to develop widespread surface faults

1 Early phase of expansion

Early in its history, Mercury's already-hot interior grew much hotter and swelled in volume as radioactive minerals in the mantle released energy as they changed their form.



2 Cooling and contraction

Thanks to its thin mantle, the heating effect of radioactive elements dwindled rapidly and the loss of heat became dominant. As the planet's interior cooled, it then began to shrink.

Splitting crust

As the interior expanded, Mercury's crust fractured, allowing volcanic lava to rise up and fill the gaps. These early features were later obscured by heavy asteroid bombardment.

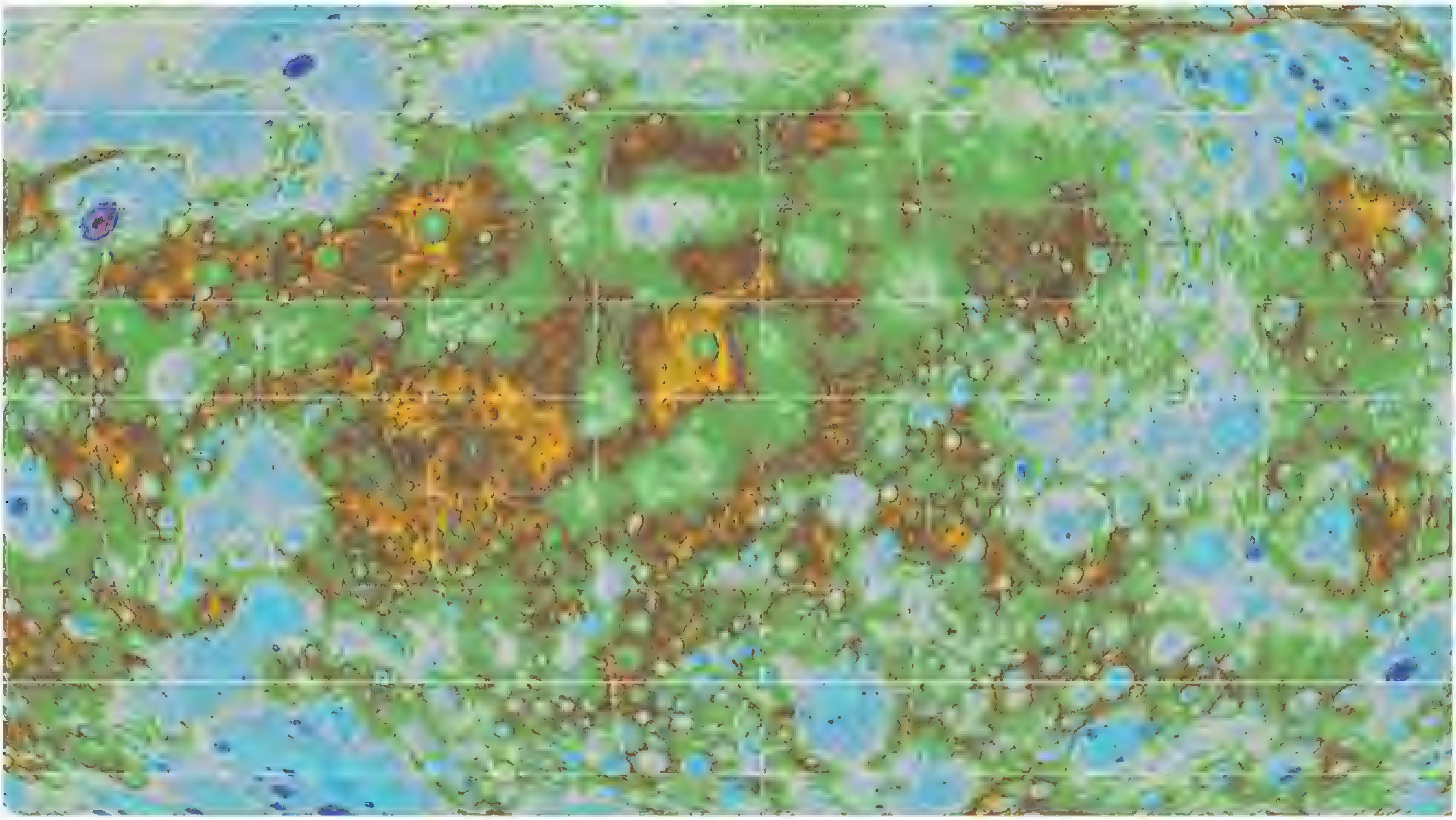
Scarp formation

Shrinking of the interior created stress as the solid crust attempted to contract. Eventually it manifested in thrust faults that pushed certain areas up above others, creating widespread scarps.

conclusions, putting them on either side of a debate that's been running since the 1970s. "Post-Mariner 10 models of Mercury's interior predicted a radius change of between five and ten kilometres (three and six miles) through its history," recalls Byrne. "But early observations suggested an actual change of between one and two kilometres (0.6 and 1.2 miles). The basic contraction models were saying one thing and the geologists something else, and until we could resolve that gulf, we couldn't really use the model to make other predictions about its history."

"We're all pretty much in agreement that the principal influence on the contraction is a slow cooling of the interior," says Watters. "But I think part of the emerging debate is the question of how slow that interior cooled. You're going to expect more contraction from a faster cooling interior. Along with colleagues, I started looking again at the Mariner 10 data in the late 1990s. There's a well-established relationship from Earth and other planets between the length of

This colour-coded elevation map from MESSENGER data shows height differences in the crust's regions. High areas are brown, yellow and red, and low areas are blue and purple



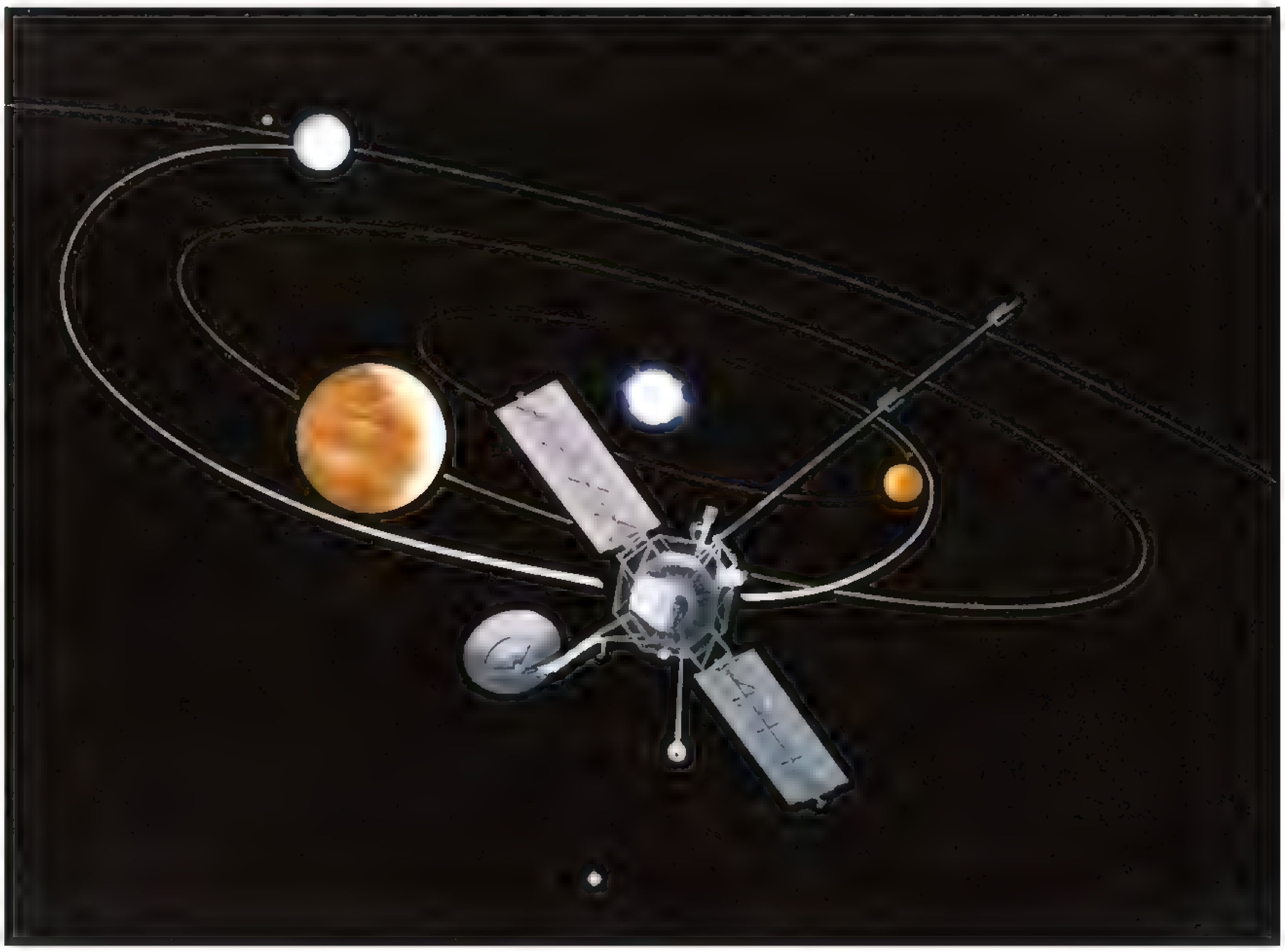
a fault and the amount of displacement that occurs along the fault, and when we applied that, we were pushing it to get to even one kilometre (0.6 miles) of shrinkage. Adding data from the early MESSENGER flybys allowed us to make a new calculation that increased the amount of shrinkage slightly, but we were still talking about one kilometre (0.6 miles) or so. Even with full maps of the surface, our estimates still don't put us above two kilometres (1.2 miles) at most."

Byrne and his colleague Christian Klimczak at the University of Georgia began to look at the problem themselves in 2012. "We mostly wanted to understand the distribution of these scarps. But once you've got that information about number and distribution, you can also make an estimate of the radius reduction using some basic assumptions. What we found using two different approaches was that the amount of shrinkage all these structures represented was somewhere between four and seven kilometres (2.5 and 4.3 miles). What's more, you can't just look at the structures on any world simply by adding up the visible scarps and making some geometric assumptions, because there's an amount of deformation anything made of rock will withstand before it starts to form lobate scarps. It's like standing on a table – the table doesn't break or even deform immediately, but you're still applying a stress to it." Byrne continues.

"Our colleagues have calculated that amount of deformation to be between a few hundred metres and perhaps two kilometres (1.2 miles), which suggests that Mercury's radius change has been somewhere between five and nine kilometres (3.1 and 5.6 miles). That's a pretty broad range and there are a lot of estimates involved, but they're educated estimates, and they've ended up with a figure that comes in way higher than those predicted before – right around what the contraction models suggest."

Watters disagrees with the idea of Mercury's crust absorbing a substantial amount of 'hidden' shrinkage before it started to form scarps – but why such a big difference in the figure the two geologists derive from the visible evidence? Watters explains it like this: "In the simplest terms, when I make a tectonic map I assign one master fault to each structure, while Paul will assign multiple faults around a single structure. I'd argue that those are secondary and tertiary features that don't contribute significantly to the total contraction."

Byrne agrees that this is at the heart of their differing results: "Tom fundamentally doesn't include all the landforms that we include, and as a result his value for the amount of radius change is considerably lower". With both scientists using the same basic principle, it all comes down to the rules they use for including scarps and other deformation features. So who is right? Byrne's estimates have the advantage of matching the long-standing models of Mercury's thermal contraction, and he argues that they help explain some of Mercury's other present-day features. "Once you allow more contraction and add in new data about the surface composition to your geological

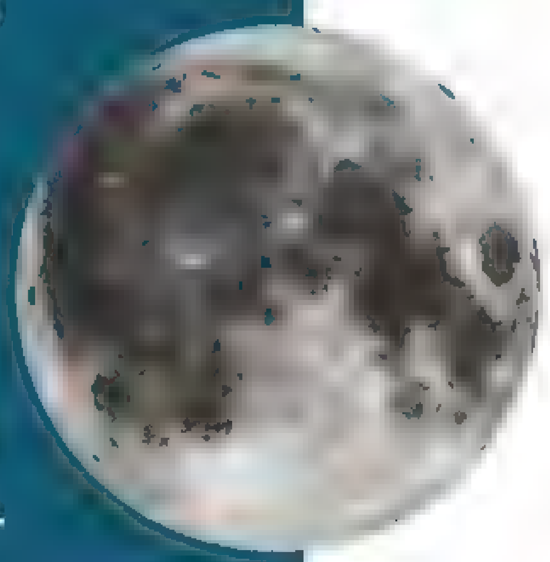


OTHER SHRINKING WORLDS

Mercury isn't the only inhabitant of the Solar System that's shrunk throughout its history

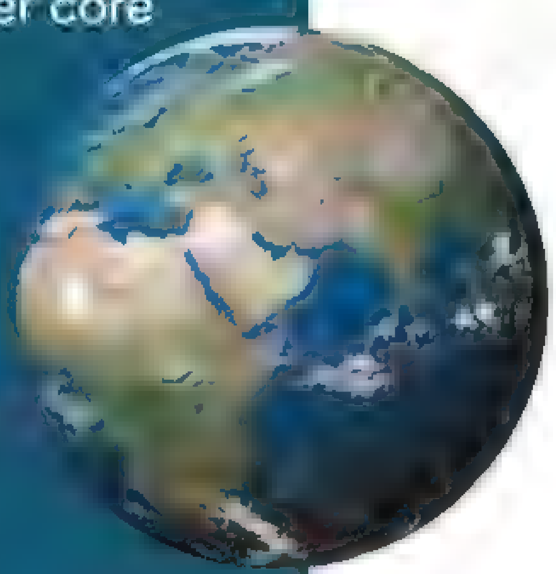
The Moon

In 2010, Watters and his colleagues studying data from the Lunar Reconnaissance Orbiter found small-scale lobate scarps on our Moon.



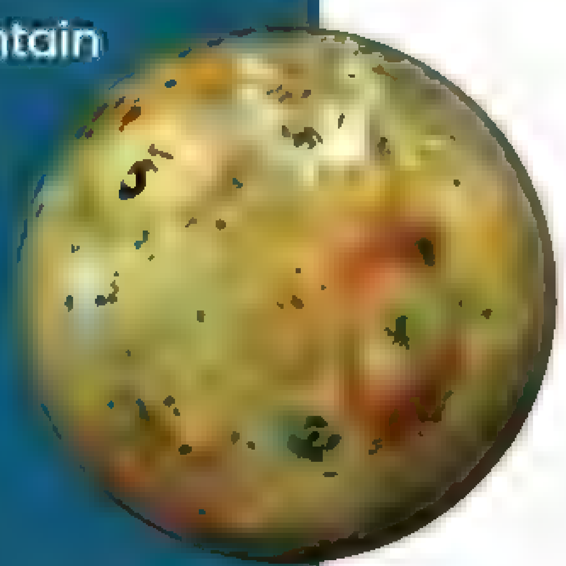
Earth

Its larger size, smaller core and deeper mantle mean that Earth has probably shrunk very little since reaching equilibrium after its formation.



Io

In 2016, researchers suggested its mountain peaks are created by faulting as the crust shrinks and collapses under the weight of volcanic lava.

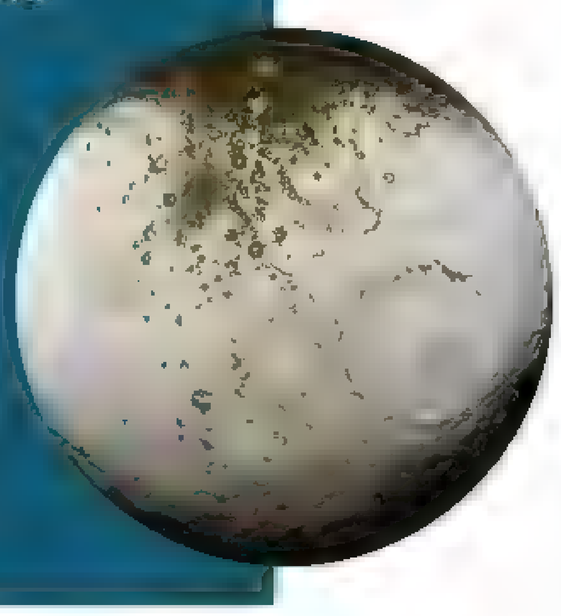


Rhea

The moon's larger size likely caused it to shrink and grow denser earlier in its history, changing the structure of its interior into a far more solid ice.

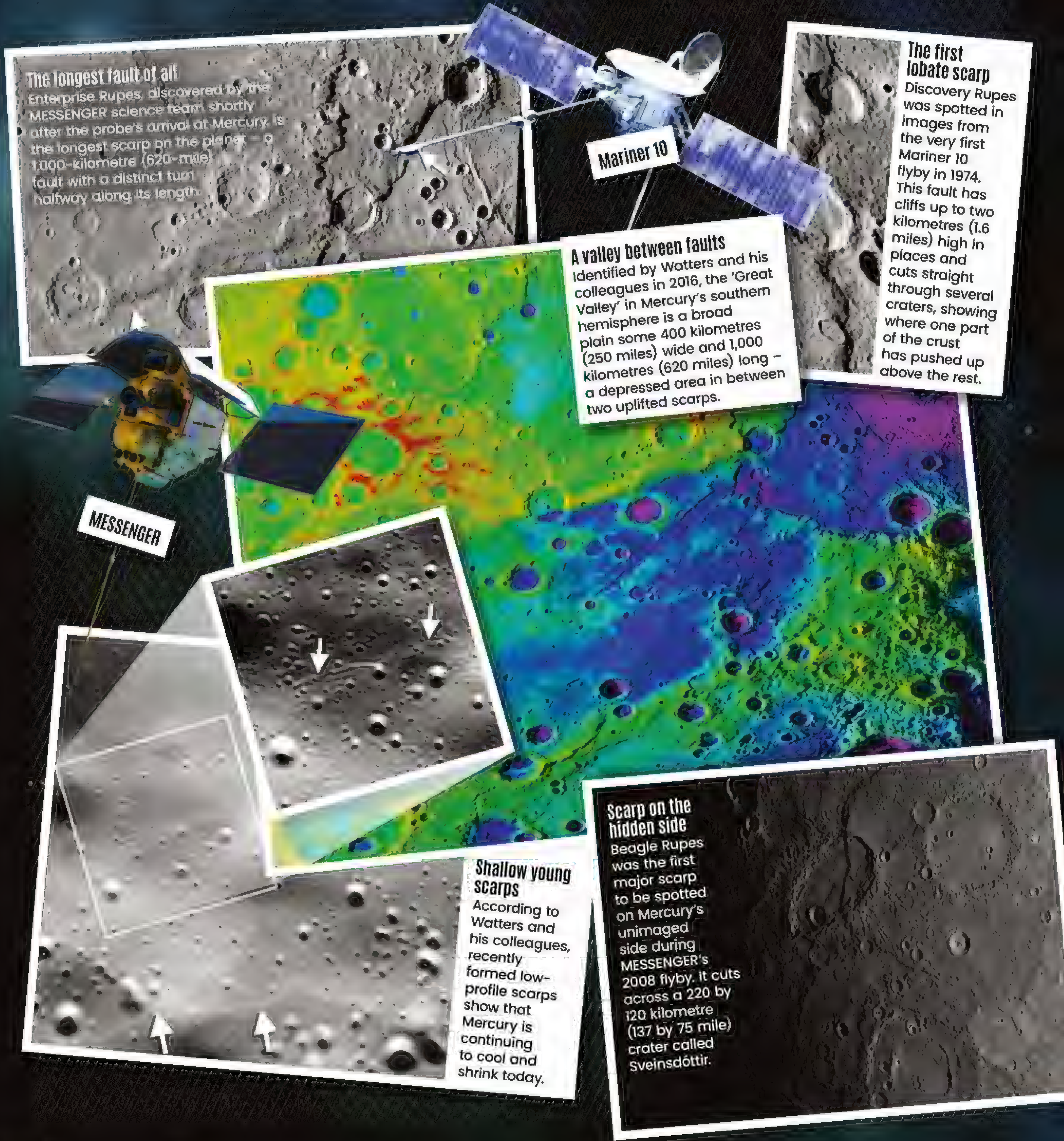
Iapetus

One explanation for the moon's walnut-like shape is that it once had a pronounced equatorial bulge that later shrank back, except for at the equator itself.



POSTCARDS FROM MERCURY

The pint-sized planet is home to some spectacular surface features, including many that point to its history of shrinking



The longest fault of all

Enterprise Rupes, discovered by the MESSENGER science team shortly after the probe's arrival at Mercury, is the longest scarp on the planet – a 1,000-kilometre (620-mile) fault with a distinct turn halfway along its length.

The first lobate scarp

Discovery Rupes was spotted in images from the very first Mariner 10 flyby in 1974. This fault has cliffs up to two kilometres (1.6 miles) high in places and cuts straight through several craters, showing where one part of the crust has pushed up above the rest.

A valley between faults

Identified by Watters and his colleagues in 2016, the 'Great Valley' in Mercury's southern hemisphere is a broad plain some 400 kilometres (250 miles) wide and 1,000 kilometres (620 miles) long – a depressed area in between two uplifted scarps.

Shallow young scarps

According to Watters and his colleagues, recently formed low-profile scarps show that Mercury is continuing to cool and shrink today.

Scarp on the hidden side

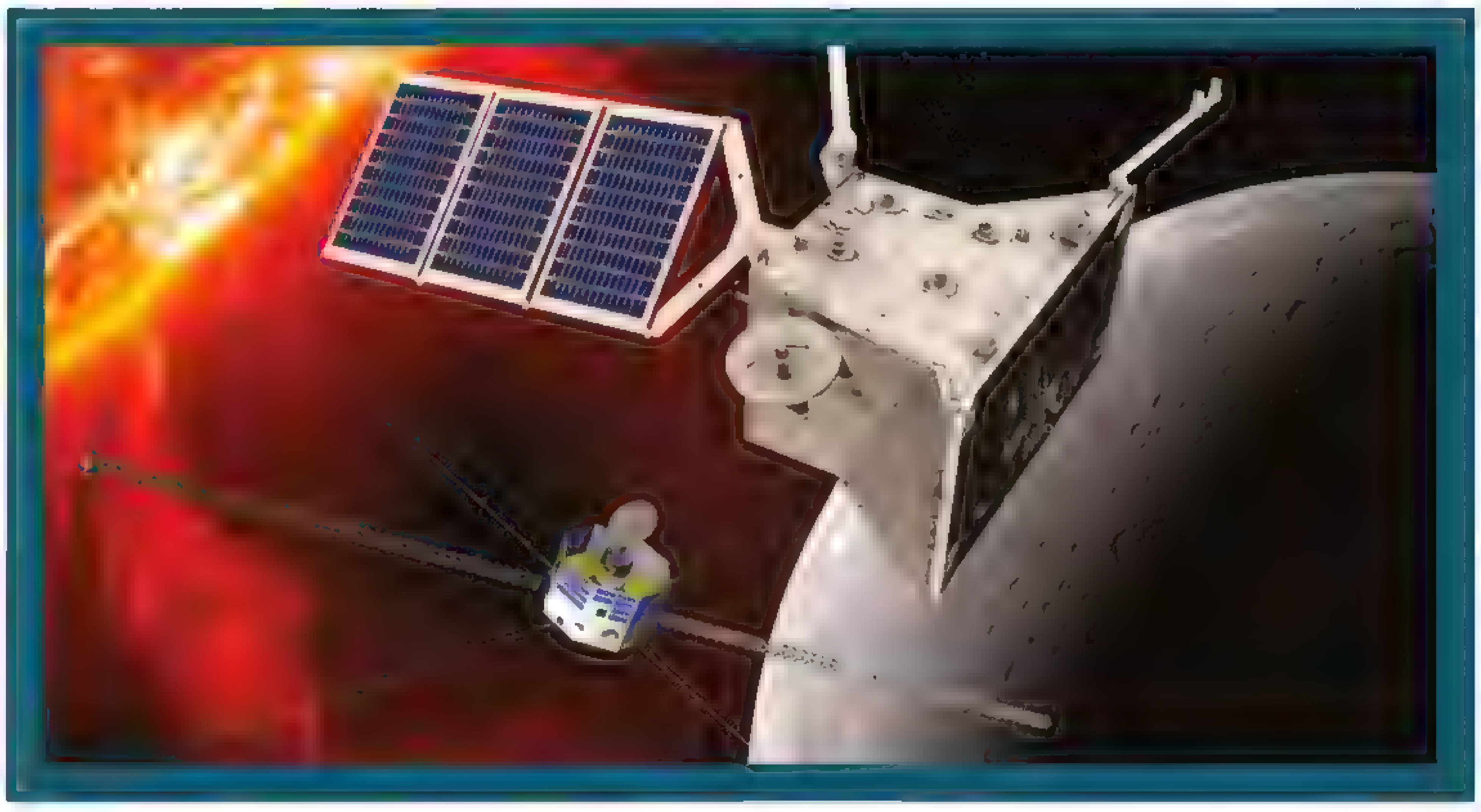
Beagle Rupes was the first major scarp to be spotted on Mercury's unimaged side during MESSENGER's 2008 flyby. It cuts across a 220 by 120 kilometre (137 by 75 mile) crater called Sveinsdóttir.

models, you find a lot of things begin to line up – for instance, explaining the presence of the magnetic field today," says Byrne. "If these new models are more consistent with our observations, it might suggest that this measurement is more robust than previous ones."

Watters suggests that some of MESSENGER's final discoveries about the planet could undermine long-standing models of its cooling, and instead chime better with his measurements. "In the last phase of the mission we were able to lower MESSENGER's orbit, and we started picking up signs of ancient, frozen magnetic fields over the volcanic plains. The assumption had previously been that Mercury's magnetism is a late-stage event, perhaps triggered by the freezing out of a solid inner core, but these volcanic rocks are about 3.7 to 3.9 billion years old. They show that Mercury has had a long-lived magnetic field for billions of years, but that doesn't really work with earlier thermal history models, which predicted fairly rapid cooling of the interior and a large amount of contraction. We're looking at an interior that's been cooling more slowly to keep the dynamo effect going."

Another intriguing discovery has been very shallow fault scarps – shallow features that can only be a couple of tens of million years old, as otherwise they'd have been eroded away by meteorite impacts. "If you couple that with a long-lived magnetic field indicating slow cooling, that seems to suggest that Mercury is still shrinking today," argues Watters. "I think that's radically changed the picture and makes it harder to explain the larger contraction figures." But Byrne isn't so sure: "Tom's small lobate scarps may be a modern-day manifestation of cooling and crust contraction, but there's an interesting question of why. If they're due to compression, those new structures would form instead of continuing to dump the strain into the existing faults."

MESSENGER's mission came to an end when it crashed into the planet's surface in April 2015, so this seems like an argument that could run and run. "I think the issue is only really going to be resolved if and when another group revisits the question from scratch and produces their own maps," admits Byrne. "That would be a useful test for both of our maps and our criteria for including landforms." BepiColombo, a joint European and Japanese mission to Mercury, should arrive in orbit around the tiny planet late 2026. With a more circular orbit than MESSENGER, the mission should provide better data about Mercury's terrain and magnetism – particularly in the southern hemisphere where the longest and deepest lobate scarps seem to be concentrated, and may finally provide the data needed to put this matter to rest.



BepiColombo, which was launched in 2018, consists of the European-built Mercury Planet Orbiter and Japan's Mercury Magnetospheric Orbiter

Giles Sparrow
Space science writer
The author of over 20 books on popular science, Giles holds a degree in astronomy and is an editor specialising in science and technology.

FOCUS ON

THE MYSTERY OF THE GREAT BLUE SPOT DEEPENS WITH A STRANGELY FLUCTUATING JET

A magnetic blemish on Jupiter is being investigated

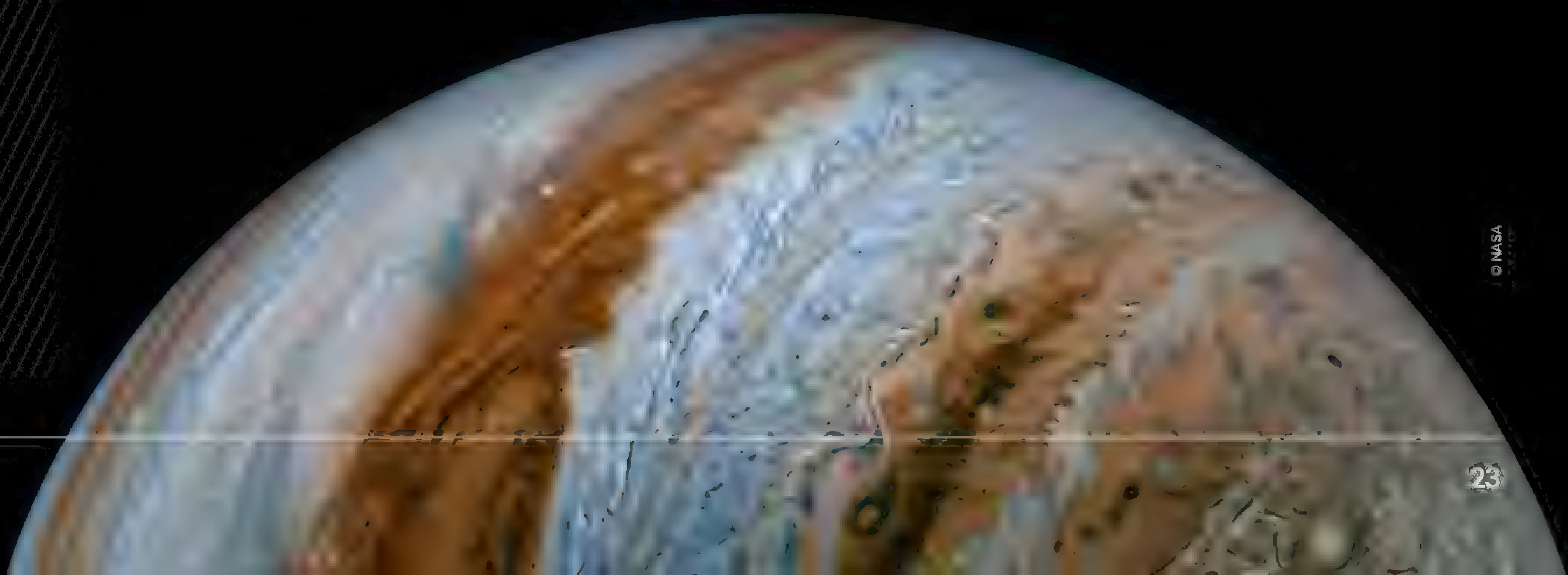
The mysterious workings of Jupiter's intense magnetic field are coming to light thanks to a tiny jet buried deep in the gas giant's atmosphere. Every four years, this jet appears to fluctuate like a wave. While it's not yet clear what drives this atmospheric jet, new findings reveal some clues about the invisible complex workings of an intense area of magnetism near Jupiter's equator, dubbed the 'Great Blue Spot'. This region isn't actually blue – the name comes from the colour scale scientists use to build maps of Jupiter's magnetic field.

Unlike Earth's magnetic field, the gas giant's field isn't symmetric with its rotational axis. This asymmetry is so pronounced, in fact, that the Great Blue Spot can even be likened to a second south pole poking out from the planet's equator. It also appears that part of the region is getting swept westward by one jet while other parts are being tugged at by winds flowing eastward. "It's a mystery," admitted Yohai Kaspi, a professor of Earth and planetary sciences at the Weizmann Institute of Science in Israel and a co-investigator of NASA's Juno mission. "We don't know why that place has that kind of an anomaly."

In a paper published 6 March 2024 in *Nature*, scientists may have offered some more insight into the Great Blue Spot. They used data sent home from the Juno probe sent to investigate Jupiter, as it had mapped the Great Blue Spot during a series of targeted flybys conducted during its extended mission. Much like ocean waves that change their speed as they move, the new finding suggests there may be wave-like behaviour deep inside Jupiter's metallic core that could power the observed magnetic field, study lead author Jeremy Bloxham of Harvard University said. "These changes can be explained in large part by an eastward drift of the spot, but as reported in this paper, that rate of drift is fluctuating."

Scientists previously knew that this cluster of intense magnetic fields drifts more than anywhere else on the gas planet thanks to strong winds blowing right from its turbulent 'surface' to 3,000 kilometres (1,860 miles) deep within the gas giant. At that deepest point, Jupiter's intense magnetic field is thought to dampen these winds. The newfound jet may even be drifting at a miniscule scale of tens of centimetres per second in that area, as opposed to other jets on the surface which travel many times faster.

Still, the finding is a "very marginal measurement," said Kaspi, who was not involved with the paper. He says it's better thought of as an initial result within the noise threshold, as scientists don't yet have enough data to conclude the jet fluctuates precisely every four years. "If your data is just from five years, you can't really say anything about a four-year period." More observations from Juno could deliver certainty soon, which would ultimately help scientists better understand the dynamo that powers Jupiter's complex magnetic field.



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MYSTERIES OF THE UNIVERSE

DID VENUS ONCE HAVE A MOON?

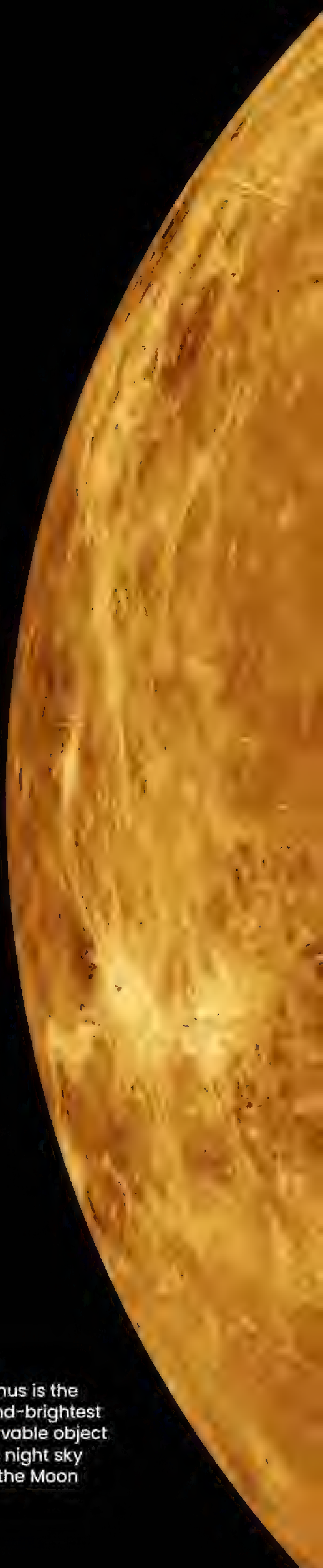
It's well known for having no natural satellite today, but did an ancient companion have a big influence on the planet?

Reported by David Crookes

It's long been established that Venus, like Mercury, does not have a moon. But does that mean the celestial body has always been entirely alone? Not quite. In 2002, a quasi-satellite was discovered by Brian A. Skiff at Lowell Observatory. Named Zoozve in 2024 because the original designation of 2002 VE68 was misread by artist Alex Foster when he was designing a space poster, it was found to be an asteroid with an orbit dictated by Venus's gravitational pull. It's termed quasi because it primarily heads towards and around the Sun, passing within the orbit of Mercury as it travels. But what if Venus once had a proper, full-blown moon? What would it have been like, and what effect could it have had on the hottest planet in our Solar System?

According to Valeri Makarov at the US Naval Observatory in Washington DC and Alexey Goldin at Teza Technologies in Chicago, there's every chance that Venus had an ancient moon that has long since been destroyed. This hypothetical body has a name – Neith – and the pair reckon it may well have played a big part in the current state of Venus, which could be an interesting explanation for one of the planet's most mysterious phenomena.

Venus is similar to Earth in many ways. Its mass, density, volume and size are closely matched, and this has led to a belief that both planets share a common origin, having formed out of a condensing nebulosity around 4.5 billion years ago. Yet Venus is also very different. It has a scorching surface temperature of



Venus is the second-brightest observable object in the night sky after the Moon

VENUS BY NUMBERS

It's the
2nd
planet from the Sun

It has
zero
moons

But there is
one
quasi-moon

Two
The number of planets that rotate clockwise

A day on Venus is
243
Earth days

Venus rotates at just
four
miles per hour at the equator

The Soviet Union sent probes to Venus between
1961 and **1981**

Venus's surface temperature is
475
degrees Celsius

475 degrees Celsius (887 degrees Fahrenheit), an atmosphere rich in carbon dioxide and thick clouds of sulphuric acid. Its atmospheric pressure is 90 times that of Earth's, too.

"Venus is so close to Earth in main physical parameters, but it's absolutely uninhabitable," Makarov says. "Is that a catastrophic accident or a reflection of our future as a species?" To answer such questions, he has developed a keen interest in the planet over many years of research. "Venus is important for understanding the origin of life, existence of civilizations beyond the Solar System and our own destiny, perhaps," he adds. "In the Soviet Union, Venus was very high on the priority list for space exploration, with some outstanding achievements not nearly surpassed to this day."

Aside from pondering why Venus has no moon, Makarov is also intrigued that Venus rotates in the opposite direction to every other planet in the Solar System except Uranus. The pervading explanation for this has long been that Venus collided with another object in the chaos that was the early Solar System, with a good number of researchers suggesting such wayward objects could have been comets, asteroids or meteoroids – the likes of which have been known to smash into planets.

But Makarov is not convinced. "There have been a few conflicting theories of the present-day retrograde spin of Venus," he told **All About Space** magazine. "Each of them is plausible in principle, but not very likely in my opinion." Instead, he has wondered whether an object didn't actually crash into Venus, but merely influenced it. And he reckons that object could actually have been the aforementioned moon. "The problem [of Venus's retrograde motion] caught my attention several years ago when I read a paper by Jacques Laskar about the impact of atmospheric tides in the reversal of Venus's spin," Makarov says. "A few points in that paper were sticking out, and I started to think about alternative explanations.

"As far as collisions are concerned, I am not a devout believer in this theory. Too many features about the Solar System have been attached to this rather improbable scenario: our Moon presumably formed from a giant collision. Venus does not have a moon but spins in the opposite direction because of a giant collision. Mercury experienced a giant collision but it spins regularly and does not have a moon. The moons of Mars are split because of a collision, but have prograde rotation. I think there's too much stuff on that plate."

To put their theory of an ancient moon's influence to the test, Makarov and Goldin ran advanced computer simulations that introduced Neith to see what would happen to Venus in various situations. The pair focused on Venus's Hill sphere, which describes the region around a planet where orbiting objects can be gravitationally bound. The Hill radius in this case is about 160 Venus radii, as opposed to our planet which is 230 Earth radii. As they stated in their paper, published in *Universe*, they looked at how "external minor bodies in trajectories loosely co-orbital to a planet can be stochastically captured by the planet without any assistance from external perturbative forces."

In other words, they were studying the circumstances in which a body could end up in a chaotic orbit around Venus and what the effects of that would be for both the object and the planet. As such, the idea behind the research was to see if they could get to the point where Venus would end up spinning in the opposite direction to other planets in the Solar System. To do this, they tested hundreds of thousands of simulations on the assumption that Venus did once spin in the same direction as Earth, Mars, Jupiter and the rest of its neighbours. Their findings were very interesting to say the least.

One of the theories suggests Venus was struck by an object

Venus is uninhabitable now, but research suggests that may not have been the case a billion or so years ago

PLANETARY SPIN

There are eight known planets in the Solar System, and two of them rotate backwards

1 Dizzying stats

Venus rotates clockwise once on its axis every 243 days, which is the longest time of any planet, and yet it completes an orbit of the Sun in just 224.7 days.

2 Sideways

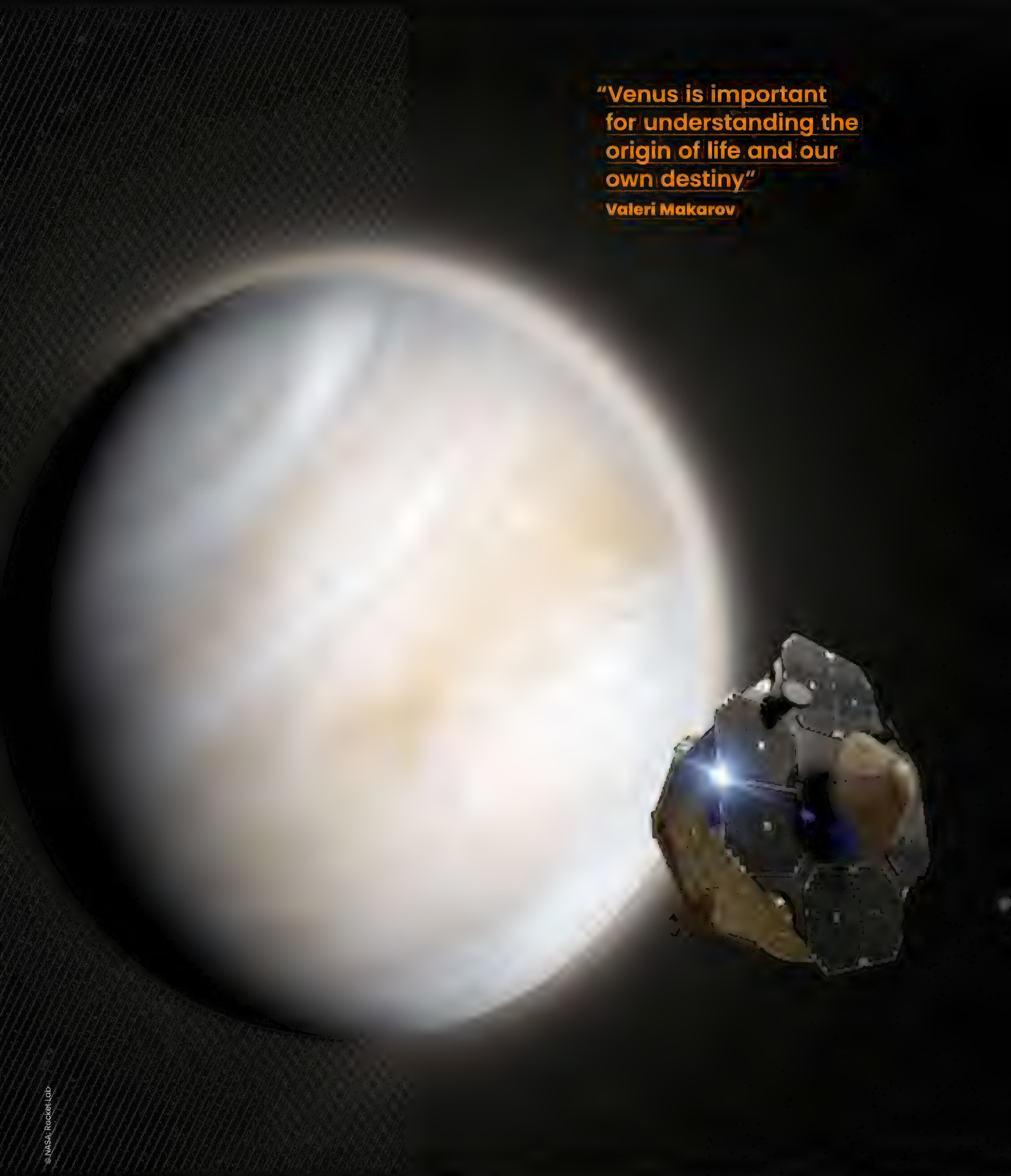
Uranus also rotates in the opposite direction to Earth. Since it's tilted at 97.77 degrees, its equator is close to being at a right angle to its orbit.

3 The right way

All of the other planets rotate anticlockwise, known as prograde rotation. This is considered to be the 'correct' way, as the Sun rotates this way as well.

"There's every chance that Venus had an ancient moon that has long since been destroyed"

> "Venus is important for understanding the origin of life and our own destiny"
> **Valeri Makarov**



© NASA; Rocket Lab

They found that if Neith was sufficiently large and had been in a retrograde orbit as it travelled past Venus around the time the Solar System formed, it was just as likely to have ended up within the Hill sphere than if it was travelling in a regular forwards orbit. "This could only happen at the very early stage following the oligarchic growth of the surviving planets, when the solar disc was still packed with a large number of smaller bodies," Makarov says.

If the moon was captured in retrograde then it would have a different effect on Venus than if it was captured in prograde. "The difference is that a retrograde moon interacts with the prograde debris disc orbiting Venus, moving against the flow of particles, which increases the rate of dissipation of kinetic energy via dynamical friction," Makarov explains. "This shortens the characteristic time of the initial moon's descent towards Venus."

The scientists noted that the planetesimal would have hung around for quite some time as it became Venus's temporary moon – anything from 100,000 to a million years. "The time scale is not known to us; this requires more detailed computations and knowledge of basic rheological parameters of Venus's mantle. It also depends on the initial mass of the moon, which is not known," Makarov says.

That would have been more than enough time for the moon to have affected Venus, since it would have acted in much the same way as Earth's Moon. Just as our Moon gains angular momentum from tidal drag, the effect of which is a slowing down of Earth's rotation to the point that it extends a day by just under two milliseconds every 100 years, so Venus's temporary moon would have caused that planet's rotation to slow. And it was able to hang around because it would have made frequent incursions into the closer area around the planet. "The fast shrinkage of the initial chaotic orbit is important to avoid stochastic ejection of the captured moon," Makarov explains.

According to the theory, as the moon created tides which slowed the spin of Venus, the planet eventually came to a standstill for a brief period before reversing direction, explaining how Venus would have begun to spin the other way. "It's possible that such retrograde captures happened many times and with other planets, but the candidate moons could not break their orbital velocity fast enough to become permanent satellites," Makarov says.

Over time, with the process continuing, the captured moon would have frequently collided with the disc material around Venus, which when combined with the planet's gravity, would have caused the moon to break up. Bits of the moon would have rained down on Venus's surface, and that would also explain why the planet does not have a natural satellite today. "Venus's moon would have descended to the Roche radius and been torn apart by tidal forces," Makarov explains. "The remaining material would most likely have been deposited on Venus's surface."

By that point, the 'damage' would have been done. In this situation, Venus would have been forever doomed to rotate in the opposite direction – which is exactly what we see – but we won't know for certain if this situation is correct because there has long been an absence of data, and it may yet be some time before we ever get sufficient evidence. But what consequences are there for a planet that ends up capturing a retrograde moon? According to Makarov, they could be dire. "Our Moon is perhaps crucially important for the emergence of advanced biological life on Earth. When life appeared on Earth, the Moon was much closer, at around six Earth radii," he says. "If it were retrograde, life would not have a chance because of the excessive tidal heating, catastrophic destruction and loss of atmosphere."

PUTTING VENUS IN A SPIN

What caused Venus to rotate clockwise?

Venus was hit by a celestial object

Many astronomers suggest that in the early Solar System, Venus was struck by a celestial object large enough to give the planet such an almighty knock that it began to spin in the opposite direction. In this scenario, the object may have been as big as Venus itself.

It was a victim of early instability

The early Solar System was chaotic – as you'd expect with so many objects being flung around and many celestial bodies being formed. With lots of interactions between planets, there's a chance that Venus was eventually nudged into rotating a different way.

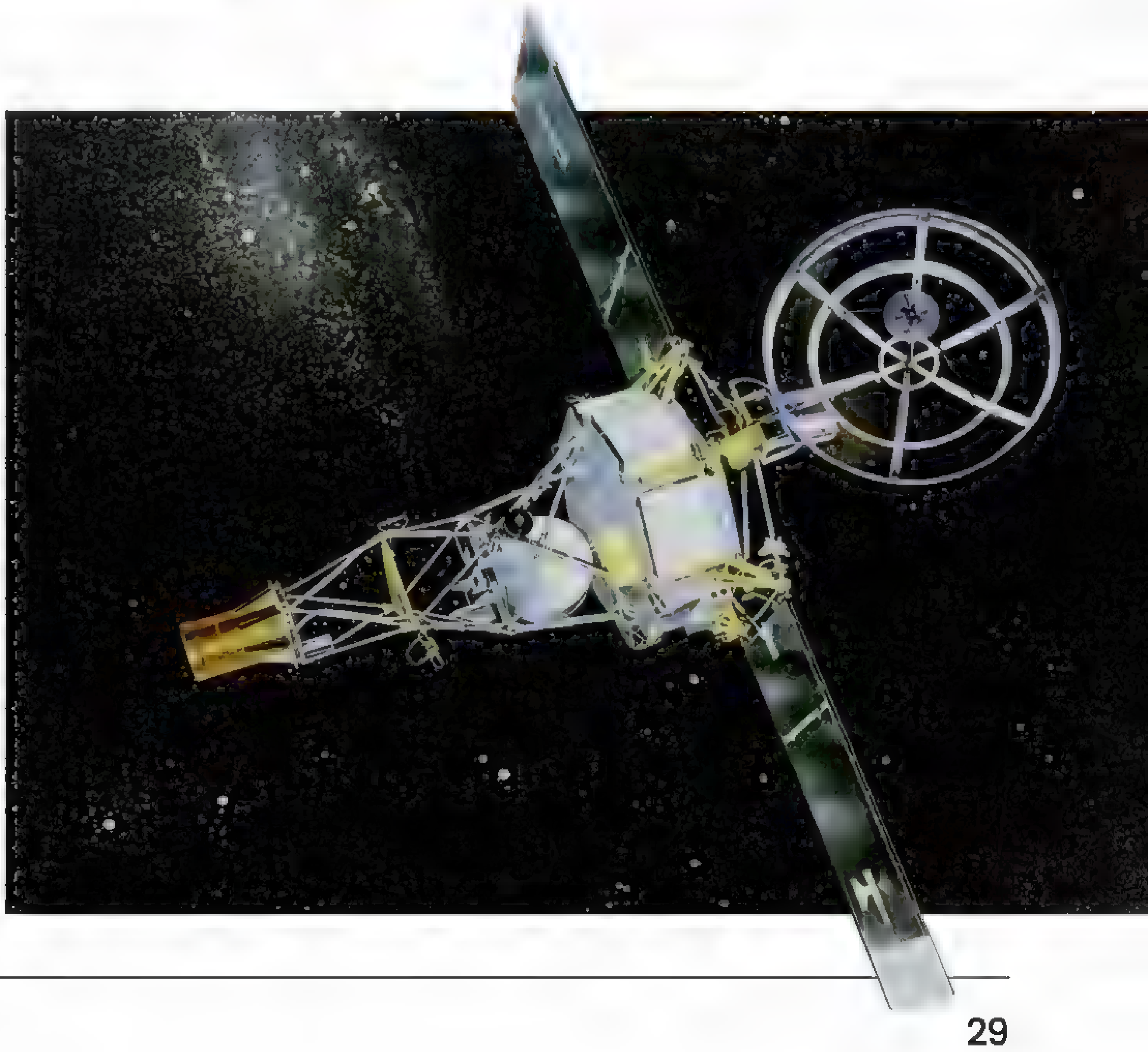
An ancient moon dragged it backwards

Also explaining why Venus doesn't have a moon, this theory suggests that an ancient moon exerted a gravitational influence on the planet, slowing down its anticlockwise spin to the point that it then began to spin clockwise. The moon then broke up, never to be seen again.

David Crookes

Science and technology journalist

David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.



A number of probes have passed Venus, including Mariner 2

More information about Venus could be provided by Rocket Lab's uncrewed Venus Life Finder, due to launch in 2026

MYSTERIES OF THE UNIVERSE

IS THERE ANOTHER PLANET BEYOND NEPTUNE?

There are now five lines of evidence suggesting the existence of Planet Nine

Pluto used to be thought of as the ninth planet in the Solar System, but in 2006 the International Astronomical Union created an official definition for planets and decided Pluto didn't fit all of the conditions. The upshot was a reclassification of the body discovered by Clyde Tombaugh at Lowell Observatory in 1930, with Pluto being labelled a 'dwarf planet' instead. But that's not to say a ninth planet doesn't actually exist. In fact, as time goes on, there's more and more evidence to suggest one is very much out there.

The search for a ninth planet has been ongoing for some time. American astronomer Percival Lowell spent the last decade of his life looking for a hypothetical planet beyond Neptune – the so-called Planet X. It was thought that another planet in the outer reaches of the Solar System would account for the apparent irregularities in the orbits of Uranus and Neptune, and when Pluto was discovered it seemed the search was over.

In 1978, however, Pluto was dismissed as the cosmic influencer because it was too small to have any gravitational influence. Then it was found that Uranus's orbit only differed from predictions because the calculated mass of Neptune had been incorrect. For a while, the idea that there could be another planet in the Solar System was put on the back burner – that is until scientists searched for a potential explanation for why some of the dwarf planets and other tiny icy objects follow orbits that cluster together. Faced with that conundrum, another planet in the far reaches of the Solar System seemed entirely plausible.

At the forefront of this research are Mike Brown and Konstantin Batygin, astronomers at the California Institute of Technology. As it happens, Brown in particular is well known for having played a role in the downgrading of Pluto – he calls himself the 'Pluto killer' – but after the pair gave an interview claiming the existence of Planet Nine on 20 January 2016, they've been associated with it ever since. It's a theory that has continued to thunder along in the years since.

When Brown and Batygin put forward their reasoning, they pointed to a large object called Sedna – another dwarf planet orbiting the Sun beyond the orbit of Neptune. It had been discovered in 2003, partly by Brown, and observations noted that it travelled in an unusual, elongated orbit, taking 11,400 years to complete. Brown and Batygin suggested that this trans-Neptunian object (TNO) was set on this particular course due to a close gravitational encounter with Planet Nine when the Solar System was being formed. What's more, they said the hypothetical planet may have influenced another five objects.

For this to happen, the planet would need to be big. The pair suggested it would have a mass between five and ten times that of Earth, although it's now believed it could be five or six times Earth's mass and closer than originally thought. And yet despite the size and advancing technology, Planet Nine has never been directly observed. There's always hope – Brown has often suggested that it's within a year or two

PLANET NINE BY NUMBERS

The Solar System has

8

major planets

And Planet Nine would be the

9TH

Planet Nine could be

SIX

times more massive than Earth

It might orbit

20

times farther from the Sun than Neptune

Planet Nine would take about

7,400

years to orbit the Sun

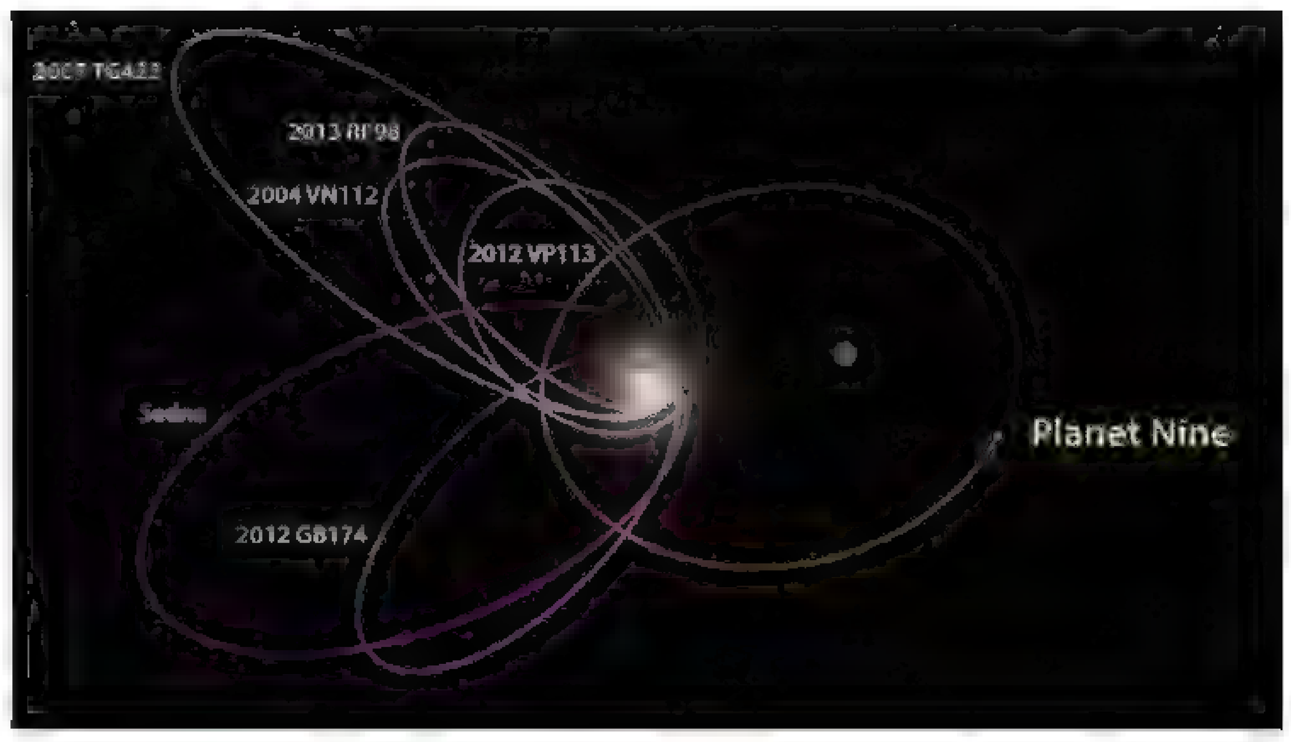
from being found – but as it stands, scientists are still relying on computer simulations to further the case.

One problem is the vast distance that Planet Nine would be from the Sun. "Simply put, Planet Nine is very distant and extraordinarily dim," Batygin told **All About Space** magazine. "The challenge of directly detecting it is difficult to appreciate without seeing first-hand how actually complex the observation process is, especially when looking for the proverbial needle in a haystack. What we have for now is gravitational evidence for Planet Nine."

When Batygin and Brown came up with their planetary proposal in 2016, they outlined four lines of evidence. They pointed to the alignment of the orbital planes of distant TNOs, the clustering of the longitudes of perihelion – that is, the alignment of major axes of long-period orbits – an excitement of high inclinations of large, semi-major-axis minor bodies and a flux of retrograde centaurs in the outer Solar System. Centaurs are small, icy objects orbiting the Sun between Jupiter and Neptune.

These icy bodies are hundreds of times farther from the Sun than Earth, and their elongated orbits cross that of Neptune to the point that they are sometimes closer to the Sun than the ice giant. The idea is that, because they are so far away from Neptune's gravitational tides, a hypothetical Planet Nine exerts a great influence on them, effectively sending the objects Neptune's way. Crucially, Neptune's gravity eventually scatters these objects, yet it continues encountering them. This suggests that Planet Nine is still very much out there, its gravity having a major effect.

Brown and Batygin have been studying these particular TNOs along with Alessandro Morbidelli of the Observatoire de la Côte d'Azur in Nice, France, and David Nesvorný of the Southwest Research Institute in Boulder, Colorado. "This work introduces a novel, fifth line of evidence for Planet Nine, which turns out to be the most statistically significant," Batygin says. The work



Six distant objects in the Solar System orbit beyond Neptune and line up in a single direction, tilting identically away from the plane of the Solar System. In 2016, Batygin and Brown suggested Planet Nine would be needed for such a configuration

adds "the perihelion distribution of Neptune-crossing long-period TNOs," and "without Planet Nine, these five features of the outer Solar System remain mysterious".

The analysis is significant, the researchers say, suggesting it provides the strongest statistical evidence yet that Planet Nine really does exist. Until this study, astronomers seeking evidence for Planet Nine had overlooked any objects orbiting unstably due to their interactions with Neptune's gravity. But fresh thinking has potentially led to a breakthrough – one which goes a long way to clearing up a long-standing mystery.

"For the last decade, we were under the impression that only dynamically stable TNOs have a chance of maintaining a footprint of Planet Nine-induced evolution," Batygin explains. "In the new work, we decided to break the habit. What we found is that, in essence, if Planet Nine exists, it would occasionally pull the orbits of distant trans-Neptunian objects closer to the Sun to the point where they cross Neptune's orbit. Without Planet Nine, these objects can't be pushed inward past Neptune very often. However, observations show that TNOs are indeed found closer to the Sun than expected. Our detailed computer simulations show that this pattern matches the influence predicted by Planet Nine, and can't be explained otherwise."

To reach their conclusion, the scientists carried out simulations testing how various celestial bodies affected the TNOs' orbits. As well as considering passing stars and the galactic tide caused by gravitational forces within the Milky Way, they factored in Neptune and other giant planets. They found that the behaviour of the studied TNOs could only be best explained when Planet Nine was included in the modelling, although it was feasible that they temporarily fell under the influence of other planets at some time in the past.

"We carried out two suites of computer simulations that model the formation and long-term evolution of the Solar System, both with and without the

Brown and Batygin have been at the forefront of investigations into a possible Planet Nine

PLANET NINE'S PLACE

Just how would Planet Nine compare to other planets in the Solar System?

1 Five Earth masses

Planet Nine is said to be about five or six times the mass of Earth. If proven to exist, it would be the fifth-largest planet in the Solar System, dwarfing Pluto and the planets of the inner Solar System but not quite as large as Jupiter, Saturn, Uranus and Neptune.

2 Far, far away

Planet Nine would be located well beyond the orbit of Pluto and would be in a highly elongated orbit. For perspective, Neptune is 4.5 billion kilometres (2.8 billion miles) from the Sun. Planet Nine is thought to be about ten times that distance from our star.

3 Ice cold

Since it's so far away from the Sun, Planet Nine would be an icy planet with a solid core. But whether it would be rocky like Earth or gaseous like Neptune is unknown. We'll only truly get a better idea if and when astronomers directly observe it.

Our knowledge of the Solar System is ever changing. This image by NASA, created in 2000, labelled Pluto as a planet and included the four large moons of Jupiter. Pluto is now classified as a dwarf planet, and as of 2023 we know there are 95 moons of Jupiter

hypothesised Planet Nine," says Batygin. "In the case where Planet Nine is included, the simulations align with the observed population of long-period orbits that cross Neptune's path. On the other hand, a model of the Solar System without Planet Nine fails to reproduce these observed orbits. In essence, this difference shows that the gravitational influence of Planet Nine is required to create and sustain the flux of this trans-Neptunian population of minor bodies."

In particular, when Planet Nine is introduced into the mix, slinging the objects towards Neptune's orbit, one thing stood out. As Batygin explains: "The crux of the statistical power lies in the perihelion distribution of the observed orbits. This is what ultimately rules out a Planet Nine-free Solar System at five sigma." Conversely, without Planet Nine the galactic tides would fail to influence the TNOs past Neptune because they wouldn't be able to give it enough of a shove. Given it's clear the TNOs do cross Neptune's orbit, this suggests a planet around five times the mass of Earth would need to be present.

"Our models suggest that Planet Nine has a mass of about five Earth masses, an orbital period of about 10,000 years, an inclination of around 20 degrees and an orbital eccentricity of about 0.3," affirms Batygin. And yet it's fair to say there are still sceptics that Planet Nine exists, with some scientists believing it is likely to be a primordial black hole. Indeed, in 2020, Harvard scientists looked to see if this could be the case and came up with a test: they'd look for evidence of flares being emitted in the outer Solar System when a comet or other object is devoured by a black hole. The thing is, primordial black holes – those which formed soon after the Big Bang – are also hypothetical. In both cases, scientists are going to be relying on forthcoming technology, notably the Vera C. Rubin Observatory, set to be fully running in late 2025. "The next significant step in the quest to find Planet Nine lies with its upcoming operations," Batygin affirms.

This novel wide-field telescope, built on the summit of Cerro Pachón in Chile, features an 8.4-metre (27.6-foot) telescope, a 3,200-megapixel camera and an automated data-processing system. Its ability to monitor and explore the changing sky should prove crucial. On the one hand, the Harvard scientists say the observatory should be able to detect visible flares of light. On the other hand, those looking for evidence of Planet Nine suggest there is every chance that Planet Nine will at long last be proven. At the very least, Batygin and Brown will be looking to test all of their five lines of evidence, and they'll be hoping to rule out observational biases.

At best they may actually find Planet Nine, which means its existence will be proven beyond all doubt. And they won't need to wait all that long either. As we've noted, Brown has regularly said that Planet Nine will be proven within a year or two, and that could indeed happen. "This observatory... will revolutionise our ability to monitor the sky by scanning the entire available sky every few days," Batygin says. "The commencement of this survey should significantly accelerate our capacity to detect distant objects in our Solar System, including the elusive Planet Nine." For now, the scientists believe they are one step closer to finally solving a long-standing mystery, and there is growing confidence that they could be correct.

David Crookes

Science and technology journalist

David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.

WHAT'S PULLING CELESTIAL BODIES IN THE OUTER SOLAR SYSTEM?

Something is messing around with trans-Neptunian objects

Planet Nine

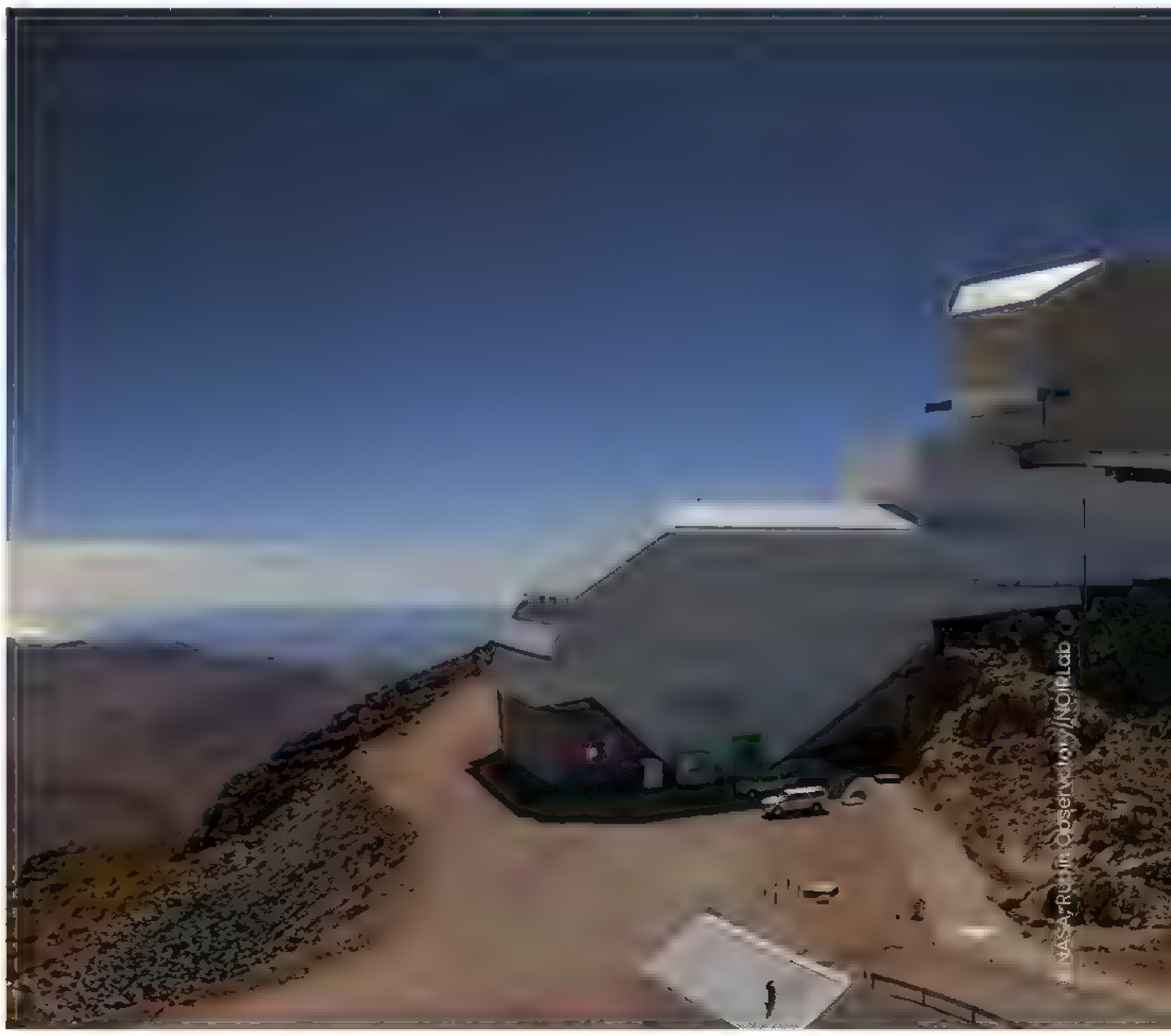
Some objects in the Kuiper Belt have unique orbits and some icy bodies are known to cross Neptune's orbit as they travel in a long loop around the Sun. Computer simulations suggest a planet with five times the mass of Earth could be causing such strange motions – in other words, Planet Nine.

Primordial black hole

Some scientists are of the opinion that Planet Nine is not actually a planet after all. They reckon it could be a primordial black hole in the outer reaches of the Solar System. It would certainly be the nearest black hole to Earth. Brown says it's a possibility, but primordial black holes are also hypothetical.

Observational bias

Trans-Neptunian objects are clustered together, and this is unusual. Planet Nine's supposed large gravity is used to explain how they came to have clustered orbits. But some scientists believe the TNOs aren't actually clustered and only look that way because of where we have pointed our telescopes.



The Vera C. Rubin Observatory will be able to rule out observational biases and potentially find Planet Nine

DID THE SUN'S TWIN WIPE OUT THE DINOSAURS?

Some 66 million years ago, an asteroid wiped prehistoric life from our planet. Could another star tied to ours have kick-started a mass extinction?

Reported by Jonathan O'Callaghan

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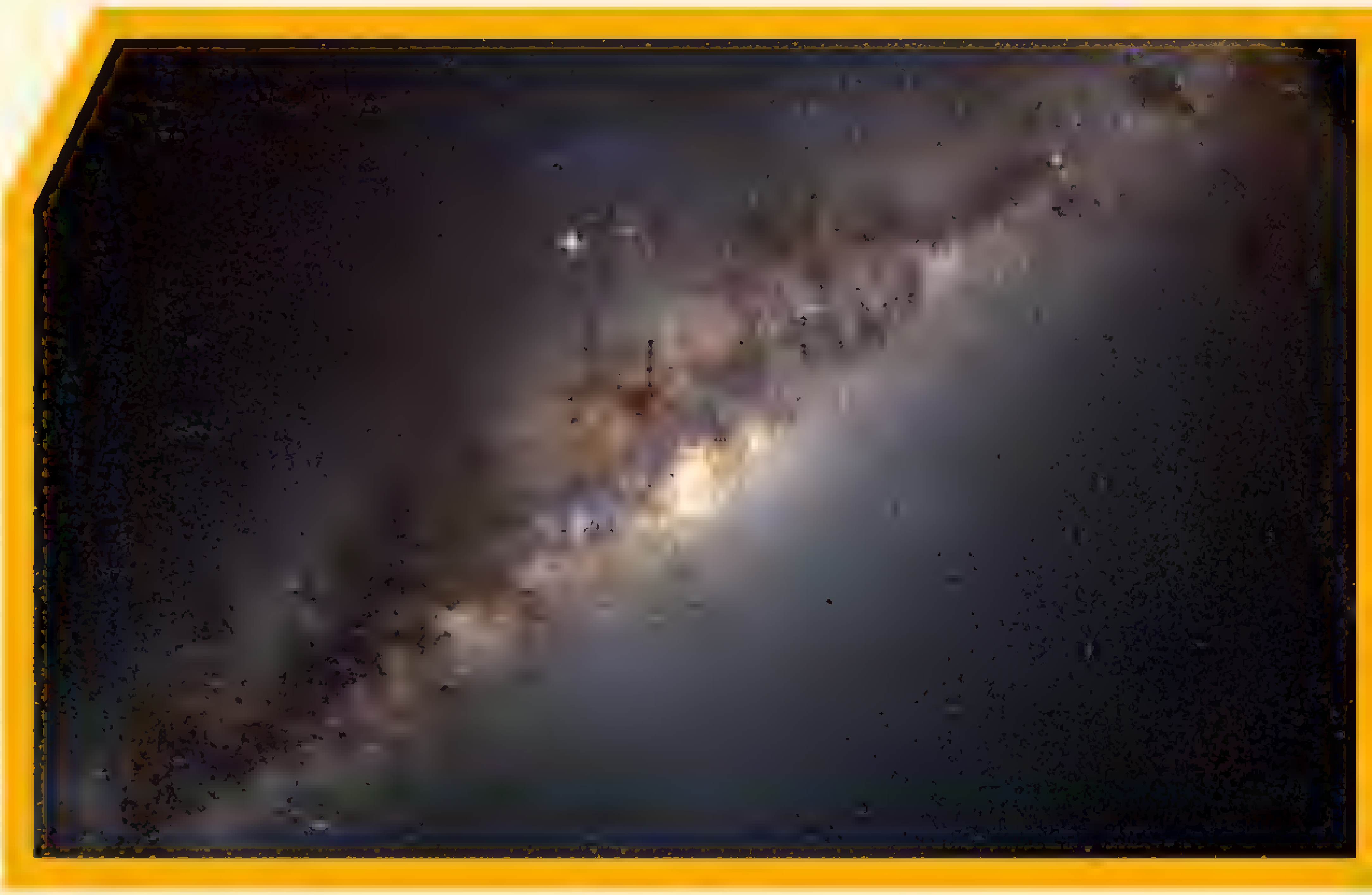
About 66 million years ago, an asteroid slammed into Earth, wiping out more than 75 per cent of all life on our planet – including the dinosaurs. What caused that asteroid to come our way has perplexed scientists for a long time. Was it just a coincidence, or were bigger powers at play? Back in 1984, a group of astronomers suggested the latter with a pretty controversial paper: Marc Davis, Piet Hut and Richard Muller proposed that every 26 to 30 million years, a companion star to our Sun would swing past the Solar System, potentially disrupting a family of asteroids and comets at our Solar System's edge – those in the Kuiper Belt and Oort Cloud – and sending some our way. They dubbed this star Nemesis, after the Greek goddess of retribution.



The idea was based on the discovery that Earth had experienced not just one, but multiple extinctions in its past. These seem to have occurred roughly every 26 to 30 million years, based on the number of large craters that have been found and aged. A number of theories were proposed for why this might be, from regular volcanic activity to a hidden giant planet in the Solar System.

The Nemesis idea provided a new theory that seemed to stand up to scrutiny. The three astronomers said it was most likely a red dwarf, the most common star in our galaxy. At less than a third of the size of the Sun and one-thousandth as bright, it would be hard to see. Its long journey would take it from its most distant point, about three light years away, to within half a light year – firmly inside the Oort Cloud, which extends out about one light year from the Sun.

Calculations from the team showed that it could be possible for such a star to maintain this orbit for about a billion years. They suggested that at present it was at its furthest point, suggesting it would swing back our way in no more than 15 million years, and possibly cause another mass extinction. Since 1984, scientists have been scouring the sky for such an object. As more and more powerful telescopes and surveys have developed, they've searched our neighbourhood for objects that could be identified as Nemesis.

The most intensive surveys of our solar neighbourhood have come from NASA's Wide-field Infrared Survey Explorer (WISE).

A There's an extremely small chance that Nemesis is located towards the centre of the Milky Way

▸ The Oort Cloud at the Solar System's edge may contain trillions of icy bodies

THE MAKING OF STARS

How these giant balls of gas and fusion come into being

1 Molecular clouds Stars are created when concentrations of interstellar dust and gas, known as molecular clouds, collapse under their own gravity.

2 Stellar pairs It's now thought that almost all stars in the universe form in pairs from the same molecular cloud, as observed in star-forming regions.

3 Cloud core The core of the molecular cloud can have a mass up to 10,000 times that of our Sun. This is the part of the cloud that collapses first.

4 Protostars The core collapses, forming multiple protostars. They take shape from clumps of matter that have up to 50 times the mass of our Sun.

5 Heating up As gas falls onto the protostar, it begins to heat up. This rapidly increases its size until it stops accreting gas and becomes stable.

6 Nuclear fusion After a few million years, the core of the protostar ignites nuclear fusion, and the object becomes a fully fledged star with a fixed mass.

Before being recommissioned to focus on the search for near-Earth objects in 2013, this space telescope was used to map the entire sky around Earth in infrared. In the process, it discovered thousands of new asteroids and comets, and even some nearby brown dwarfs – so-called failed stars that have not been able to ignite nuclear fusion in their cores.

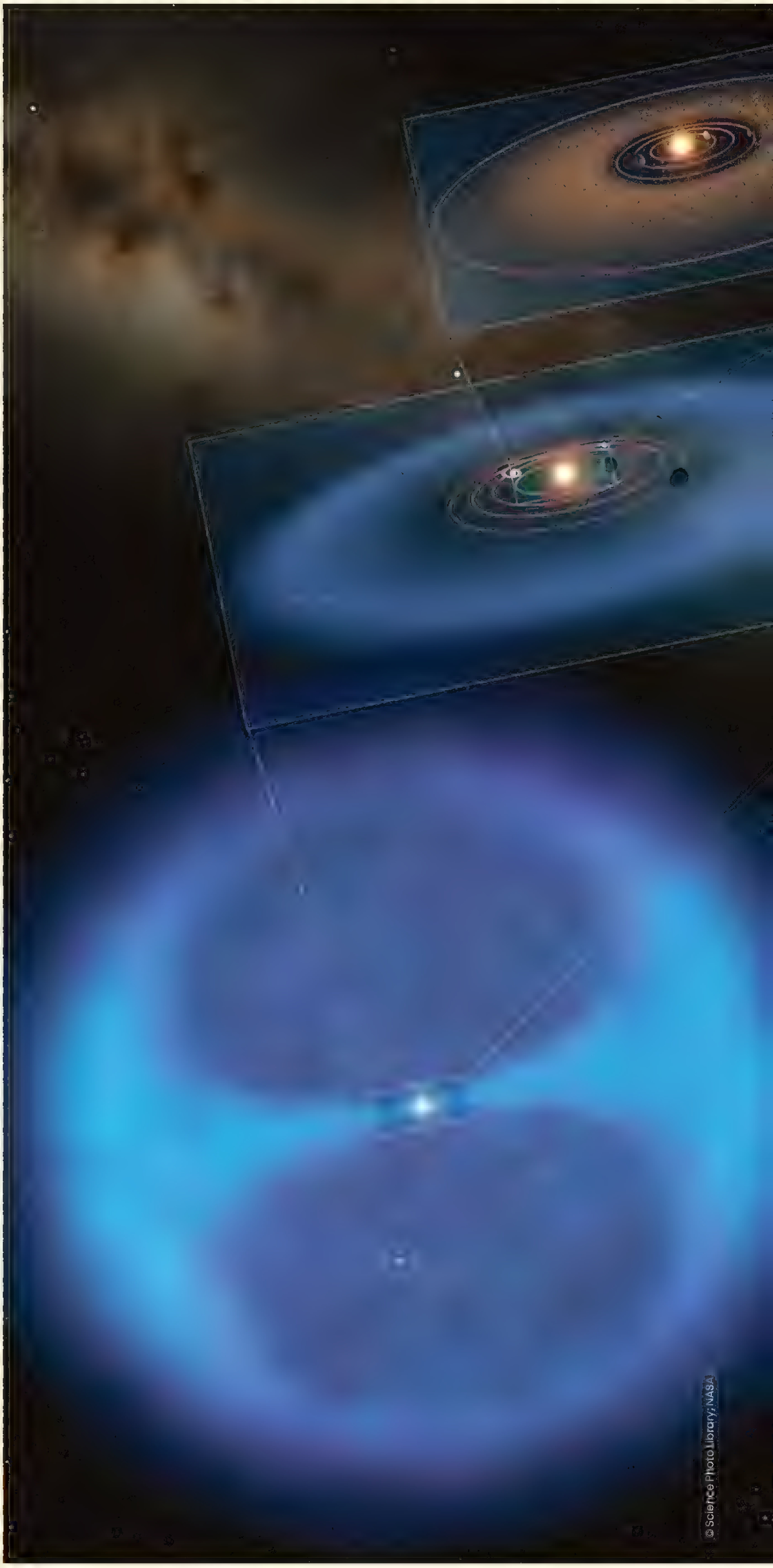
Perhaps one of WISE's most important discoveries came in 2013. That's when Kevin Luhman, an astronomer at Penn State University, found the closest star system in over a century. Together with his colleagues, he discovered a brown dwarf pair 6.5 light years away. However, the chance of this system being Nemesis was quickly quashed, with Luhman saying: "We can rule out that the new brown dwarf system is such an object because it is moving across the sky much too fast to be in orbit around the Sun".

But the discovery was important for another reason. Brown dwarfs are extremely dim. Had a star with the characteristics of Nemesis been in orbit around our Sun, it would presumably not be too difficult to spot, being much closer than this particular brown dwarf system. WISE, though, was running for roughly 13 years in orbit, and in that time found no evidence for a star in the predicted orbit of Nemesis. This dealt a pretty major blow to the idea that a star in orbit around our Sun might be causing mass extinctions.

Our Sun, however, may very well have had a twin. In a paper published in the *Monthly Notices of the Royal Astronomical Society* in June 2017, a team led by Steven Stahler from the University of California, Berkeley, suggested that all stars like our Sun formed in pairs. This was based on the discovery that our Sun did have a companion. Understandably, this brought the idea of Nemesis back to the forefront. "We are saying yes, there probably was a Nemesis a long time ago," Stahler said at the time in a statement.

Don't get too excited just yet, though. This star was almost certainly not the Nemesis we've been talking about here, being much

"In late 2016, astronomers announced they had found a star that was heading straight towards us. It's predicted to come as close as 0.2 light years to our Sun"



NEMESIS

Where this controversial star would be located if it really does exist

1 How big was the asteroid?
The dinosaur impactor is thought to have been about 10 to 15 kilometres (six to nine miles) in diameter, enough to cause a lot of damage.

2 Where the asteroid hit Earth
The crater from the asteroid that killed the dinosaurs is located near the town of Chicxulub in Mexico, which the asteroid is named after.

3 When did the asteroid impact?
The Chicxulub asteroid is thought to have hit Earth about 66 million years ago, wiping out 75 per cent of all life on Earth.

4 How big is the crater?
The resultant crater from the impact measures more than 180 kilometres (110 miles) across and is 20 kilometres (12 miles) deep.

5 Where Nemesis would be now
If it exists, Nemesis would now be at its furthest point, its aphelion, about three light years away from our Sun.

6 Disrupting the Solar System
The Oort Cloud extends one light year from the Sun; Nemesis would pass close enough to send comets our way.

7 The closest point to our Sun
At its closest point in its orbit, Nemesis was predicted to come within half a light year of our Solar System.

8 Orbit length
Nemesis was predicted to take about 26 to 30 million years to orbit, in line with the supposed periodic extinctions on Earth.

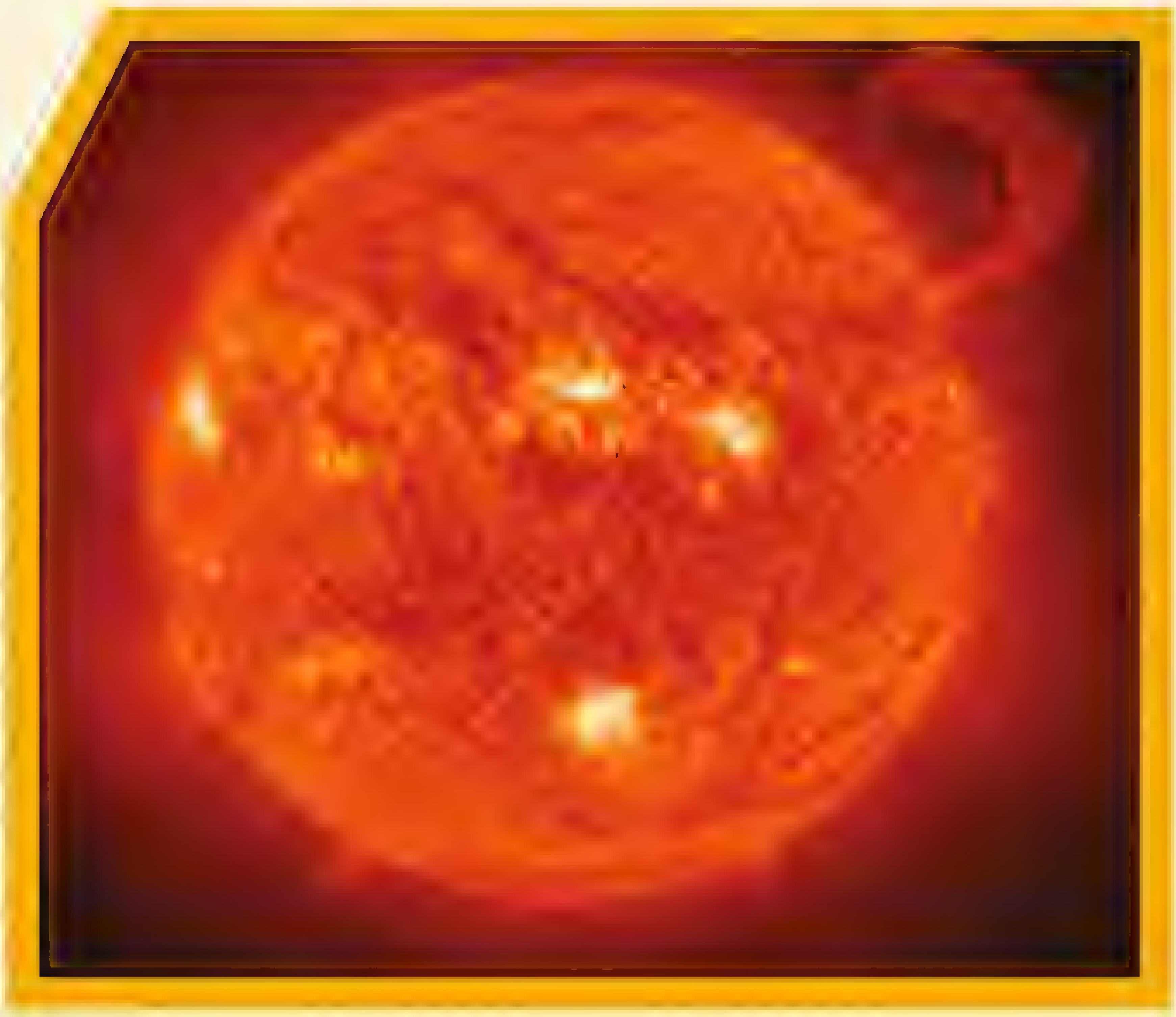
too far away and unlikely ever to return. In fact, it wasn't actually found; its existence was instead inferred from other evidence. The astronomers looked at a cloud of dust and gas in the constellation of Perseus that is a typical region that forms stars. In this region, all stars were found to seemingly be forming in pairs, leading them to suggest that this rule should hold everywhere.

This true companion, similar in mass to our Sun, would have orbited dozens of times 4.6 billion years ago when the Sun was born. After about a million years, it would have been flung away – billions of years before the dinosaurs arrived – never to return. If our Sun's true companion did exist, which seems much more likely than the existence of Nemesis, it's probably now thousands of light years away, and we are unlikely to ever find it.

"In retrospect, I shouldn't have used the name Nemesis for the Sun's old companion," Stahler told **All About Space** magazine. "It drifted away long ago, and was not related at all to the extinction of the dinosaurs. I don't think there was a star responsible for the dinosaur extinction. This star should have been found if it existed."

"I don't think there was a star responsible for the dinosaur extinction. This star should have been found if it existed"
Steven Stahler

In July 2017, astronomers announced evidence that all stars may form as pairs



That isn't to say that objects don't go without detection. Consider that dwarf planets, objects smaller than a planet but larger than an asteroid, are still being discovered today. One of these, Eris, was found back in 2005. Another, 2014 UZ224, was only announced in 2016. It's thought there could be many more – even hundreds of dwarf planets in the outer Solar System. And astronomers are busy searching for an even bigger object right now, the hypothesised Planet Nine, the existence of which has been hinted at by the strange, warped orbits of objects in the Kuiper Belt and Oort Cloud.

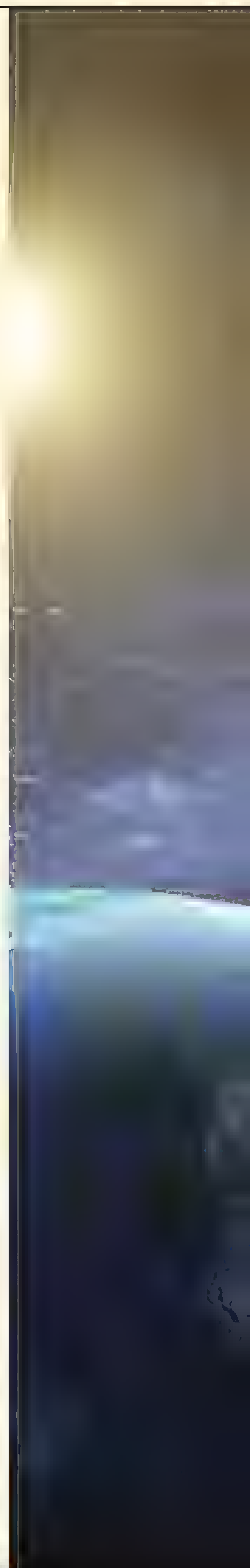
That's not all. In late 2016, astronomers announced they had found a star that was heading straight towards us. Called Gliese 710, which is currently about 64 light years from Earth, the star is predicted to come as close as 0.2 light years to our Sun in about 1.35 million years. That, as you may have calculated, puts it firmly inside the Oort Cloud. In a paper published in *Astronomy and Astrophysics*, authors Filip Berski and Piotr Dybczyński put forward the opinion that this could be the "strongest disrupting encounter in the future and history of the Solar System". Owing to its huge distance from us at the present time, however, Gliese 710 is almost certain not to be the fabled Nemesis.

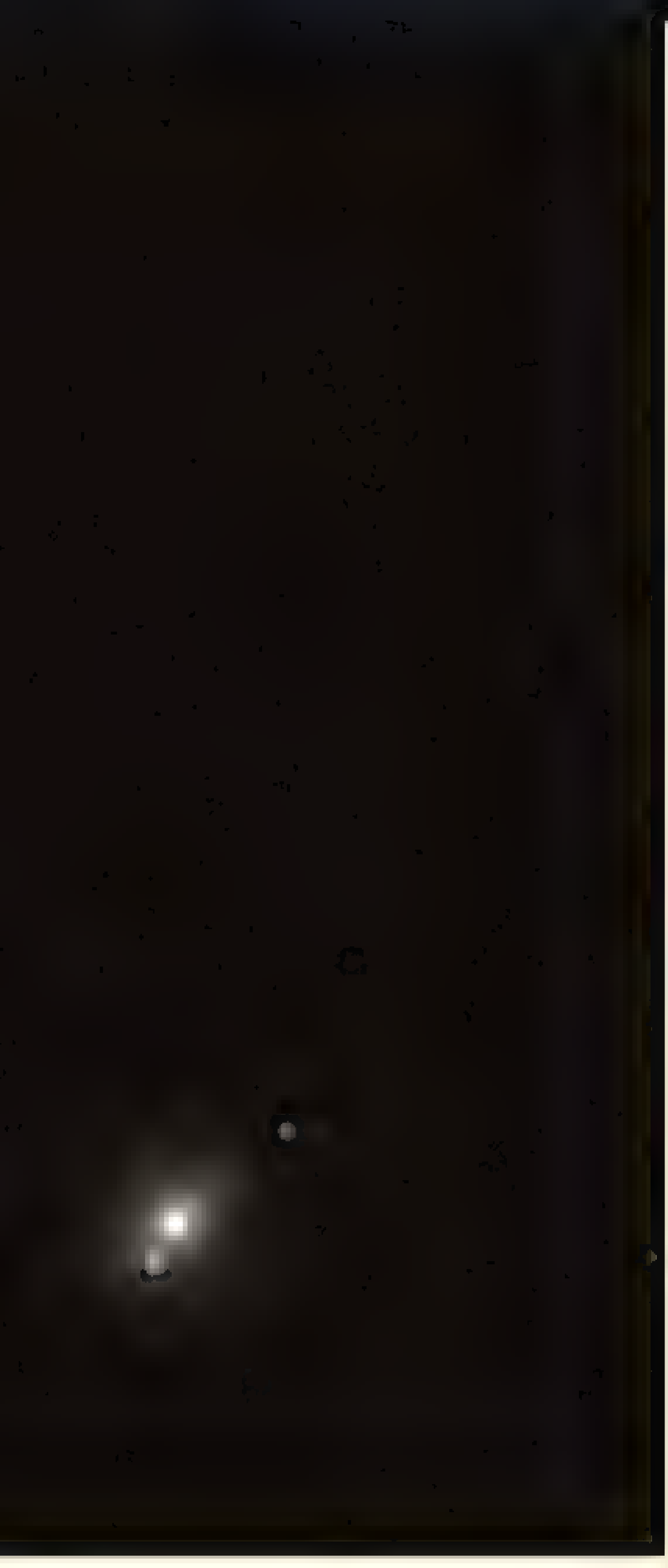
These are interesting quirks, but while they perhaps hint at hidden objects we cannot see, they are a better representation of what we can see. Astronomers have found gravitational evidence for a planet orbiting within the outer Solar System, and they can see a star dozens of light years away heading in our direction. If there was a star in orbit around our Sun, just a few light years away, we would almost certainly know about it.

Muller, of that original 1984 paper, has his own take on why this might be. He says that WISE did not look absolutely everywhere. Specifically, the craft could not see beyond the middle of the Milky Way, the galactic plane, where the stars are most dense. "If Nemesis exists, it lies close to the galactic plane," he predicts.

We asked a couple of astronomers for their thoughts on whether Nemesis could be hiding in the galactic plane. Luhman, who conducted that research in 2013, says it's pretty unlikely, although does admit there could be a reason why it hasn't been seen yet. "If the companion happened to be near a bright star when observed by WISE, it could have gone unnoticed," he says. "So there's a very small chance that a companion in the mass range proposed for Nemesis does exist. But that chance decreases every time that a new survey is performed and doesn't find such an object." David Morrison, previously a senior scientist of the Solar System Exploration Research Virtual Institute (SSERVI) at the NASA Ames Research Center, responded with a more simple answer: "No".

> "There's a very small chance that a companion in the mass range proposed for Nemesis does exist"
> **Kevin Luhman**





Our Sun may have once had a companion, but it has long since disappeared from view

We're continuing to find previously undetected objects like the dwarf planet Eris

NASA's WISE telescope, eventually known as NEOWISE, looked for Nemesis, but found no sign that it exists

If you're still not convinced, we've got one final nail in the coffin. In 2011, Coryn Bailer-Jones from the Max Planck Institute for Astronomy published a paper in the *Monthly Notices of the Royal Astronomical Society* refuting the initial idea of extinctions every 26 to 30 million years. He found that the supposed periodical patterns in extinctions were nothing more than statistical artefacts, meaning that Earth was just as likely to suffer a major impact now as it was in the past. Looking at the craters on Earth, he found absolutely no pattern to the number of impacts. If anything, he found that there was a slight increase in impacts in the last 250 million years, but certainly nothing that would point towards a regular disruption of the Solar System. "From the crater record, there is no evidence for Nemesis," he said in a statement at the time.

So where does that leave us? There's certainly a lot of evidence for dim objects being discovered in the outer Solar System, and we're also getting much better at locating other stellar-mass objects in our vicinity. However, the idea of a star in orbit around our Sun regularly causing mass extinctions seems exceedingly unlikely. We've found no observational evidence for such a star, and even the initial theory seems to be falling apart. Nemesis, like other doomsday theories, will almost certainly just be consigned to history as an interesting thought experiment, and nothing more.

Jonathan O'Callaghan

A journalist based in London, his work regularly appears in the *New York Times*, *Forbes*, *Wired*, *New Scientist* and a variety of other publications

DEEP SPACE

Go beyond the Solar System and uncover the mysteries of the universe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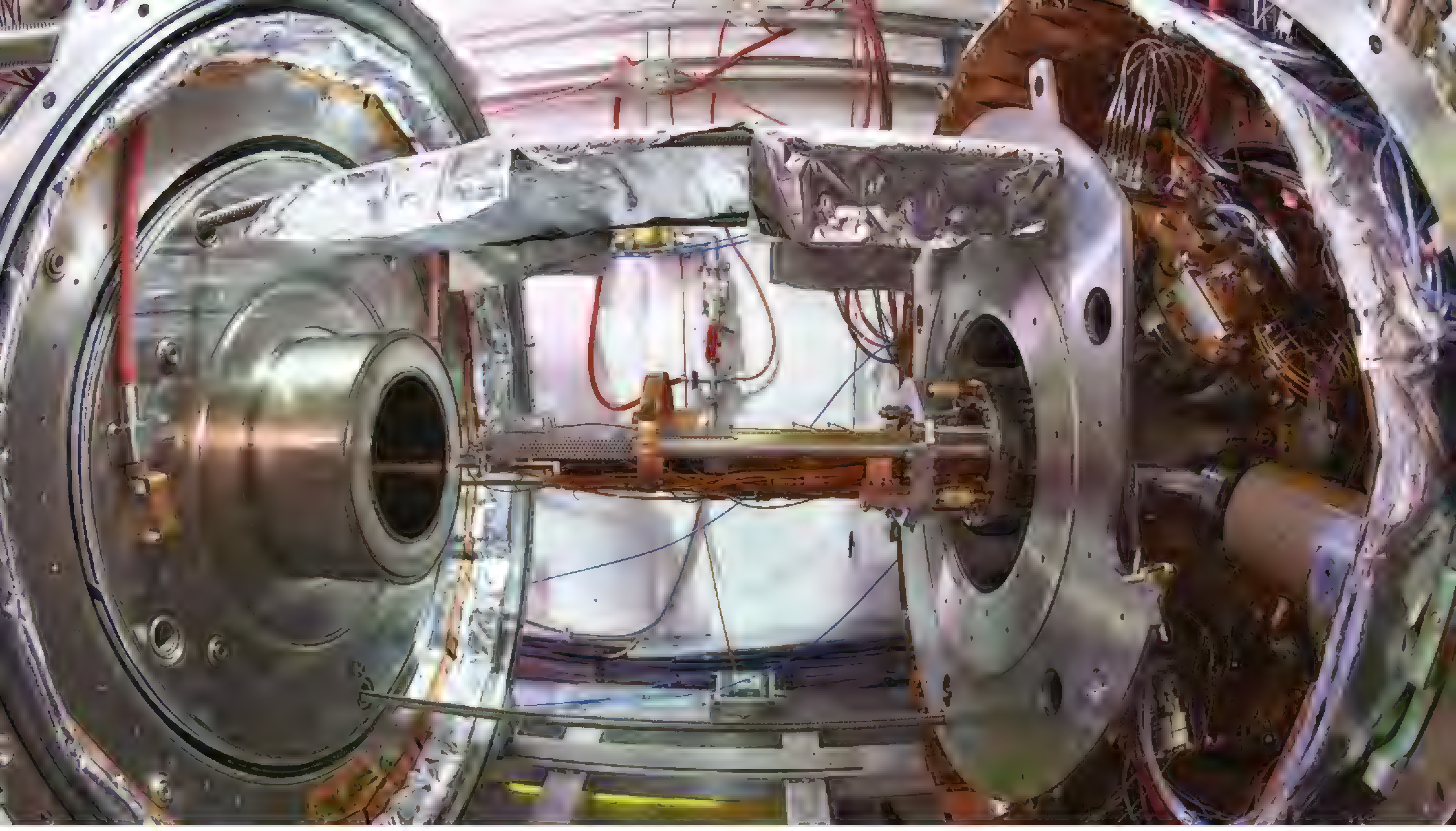
UNIV BEFOR

ERSE E TIME

Could the existence of a mirror-image cosmos before the Big Bang solve some of the biggest mysteries in astronomy?

Reported by Giles Sparrow



Our universe encompasses everything around us. Its laws of physics control every possible interaction, from the gravitational attraction that keeps planets in orbit around the Sun to the complex chemistry that gives rise to life. But for astronomers and physicists there are still some big questions about why the universe is the way it is. One of the most famous is the mystery of dark matter, which only makes its presence felt through the influence of its gravity. Another is the dominance of a certain set of subatomic particles – the familiar ones such as electrons, protons and neutrons that we call 'matter' – when there was nothing in the Big Bang itself to prevent the formation of equal amounts of 'antimatter'.

A theory developed by two Canadian physicists suggests a radical new way of looking at the universe, while also offering solutions to major questions. According to Neil Turok and Latham Boyle of the Higgs Centre for Theoretical Physics, we may be looking at one aspect of a universe of two halves. Boyle and Turok's theory, developed with Kieran Finn of the University of Manchester, originates from questions of symmetry. In physics, a symmetric process is one that produces the same result if the values of one or more properties involved are flipped or reversed. A process such as a simple interaction between particles may be symmetric under different transformations of this kind, and as a broad rule of thumb, as structures become more complex they become less symmetric.

"The way Neil and I were thinking about it is if you imagine a cartoon picture of the expanding universe, we're at the top of a sort of expanding cone, 13.8 billion years after the Big Bang," explains Boyle. "We can see back in time with astronomical observations, but not all the way back to the Big Bang. What we see there is a remarkably symmetric universe with very simple properties compared to the universe today. Those simple properties are the fundamental puzzle that early universe cosmologists want to explain – that very special initial state is clearly offering some very important clues as to what was happening in the early universe and how the universe was born. The question is, what is it trying to tell us?"

The traditional explanation for the origin of the relatively simple early universe is a hypothetical event known as inflation – a short-lived burst of violent expansion triggered a fraction of a second after the Big Bang itself, in which the universe would have grown far faster than the speed of light. The process blew up a tiny pocket of the chaotic early universe created by the Big Bang itself into the entire cosmos we see today. This 'smoothed out' conditions in general, while magnifying submicroscopic energy fluctuations into the seeds of today's galaxy clusters and superclusters.

The Canadian researchers, however, are suggesting a different picture that does away with the inflationary era: "If you follow the expanding universe back even further," explains Boyle, "then things collapse into a singularity. Ordinarily that's a mess, and you can't follow the solution beyond that. But we noticed that because of the special properties of the initial state you actually can continue to follow it back, and you get this solution that extends back. In addition to our usual universe expanding from the Big Bang, the solution has a second part which extends backwards in time from the Big Bang. Moreover, we noticed it has a property that if you flip it in time you can also reflect the two parts into each other – the part before the Big Bang is like a symmetric image of the part after the Big Bang."

One thing about this new discovery that immediately caught the researchers' eyes was how it seemed to echo a long-standing cosmological

A Physicists use the huge machines at the European Organization for Nuclear Research (CERN) in Switzerland to generate and store antimatter for experiments

B The Keck Array experiment in Antarctica

niggle one might call CPT symmetry. CPT stands for Charge, Parity and Time – a combination of three distinct types of symmetry. CPT symmetry seems fundamental to the laws of physics. When looking at any physical process, you can find an equally correct process by reversing the charges of the particles involved, effectively replacing them with their antimatter equivalents, reflecting their positions in a mirror – so-called 'parity' transformation – and running time backwards. But despite there being nothing in its laws to dictate a preference for matter particles or a particular direction in time, the universe we see around us seems to have other ideas. Time very definitely runs in just one direction, and there's far more matter than antimatter – if they were equally balanced then matter and antimatter particles would annihilate each other on contact, self-destructing in a burst of energy.

Boyle and Turok's model offers a simple and intuitive solution to the mystery. "Once we realised that we weren't looking at the whole solution, we found that the full solution could be symmetric, as we would expect." To put it simply, in the anti-universe on the 'other side' of the Big Bang, directions are flipped, time runs backwards and antimatter particles are dominant. What transforms the new model from an intriguing 'what if?' into a potential game changer are the consequences arising out of it. "These clues in the early universe seem to be a hint that we can extrapolate in a fairly simple way," continues Boyle. "So

Matter is much more abundant than antimatter in our universe

Dark matter only gives away its presence through effects such as gravitational lensing

"That initial state is clearly offering some very important clues as to what was happening in the early universe"

Latham Boyle

we elevated that to a principle: if we take the idea that the universe is CPT symmetric as a starting point, then where does that lead us? One of the things we're most excited about with this interpretation is that it gives new explanations for certain things that we've already observed about the universe but maybe don't yet have satisfying explanations for, and it also makes a couple of predictions for things we might observe in future."

One of the most intriguing is a solution to the mystery of dark matter. Since astronomical observations have ruled out other ideas, most physicists now reluctantly fall back on the loosely defined concept of weakly interacting massive particles, or WIMPs, as the source of the universe's missing mass. WIMPs could be almost anything – the name describes their basic properties of a substantial mass and an immunity to interactions with normal matter – and most potential WIMP candidates are so-called exotic particles whose existence relies on the existence of hitherto unidentified physical processes, and possibly further unidentified particles. Boyle and Turok's theory offers a simpler option, arising from its unique shift of perspective. The Standard Model of particle physics includes not only the familiar matter particles such as protons, neutrons and electrons, but also a handful of mysterious 'neutrinos' that are generated by processes such as nuclear fusion in stars. Three types of neutrino have been confirmed by physicists, and all three are 'left-handed' – a distinction relating to the way that their spin, or rotation, is always oriented in the opposite sense to their motion.

Boyle picks up the story: "We think that in addition to those three left-handed neutrinos there should be three right-handed neutrinos, and there are already some good theoretical reasons and experimental hints that these particles can exist. A right-handed neutrino is the only near-Standard Model particle whose predicted properties allow it to live for the age of the universe and which would be otherwise undetectable."

A right-handed neutrino with substantial mass might seem like an ideal candidate for dark matter, so why is it generally overlooked by cosmologists? "The reason you don't hear more about these particles is they're usually regarded as difficult to produce in the early universe," explains Boyle. "You clearly have to make enough of these particles to produce the dark matter we see today, but in the same conditions where this particle becomes stable enough to survive, it doesn't get produced – it stops talking to and interacting with all the other particles, so in theory it doesn't get made."

A CPT-symmetric universe changes the rules, however. The reasons are complex, but in essence the idea is that the symmetric universe's 'vacuum state' – which is the configuration of space-time with no particles and the lowest possible energy – is different from the one that we perceive in the non-symmetric universe we can see, and it is this mismatch that gives rise to the possibility of plentiful right-handed neutrinos. "It's analogous to Stephen Hawking's discovery of Hawking radiation," Boyle points out. "He said that a black hole is really in one state, but an observer far away defines a different vacuum state, so they see particles being emitted from the black hole. The same happens for

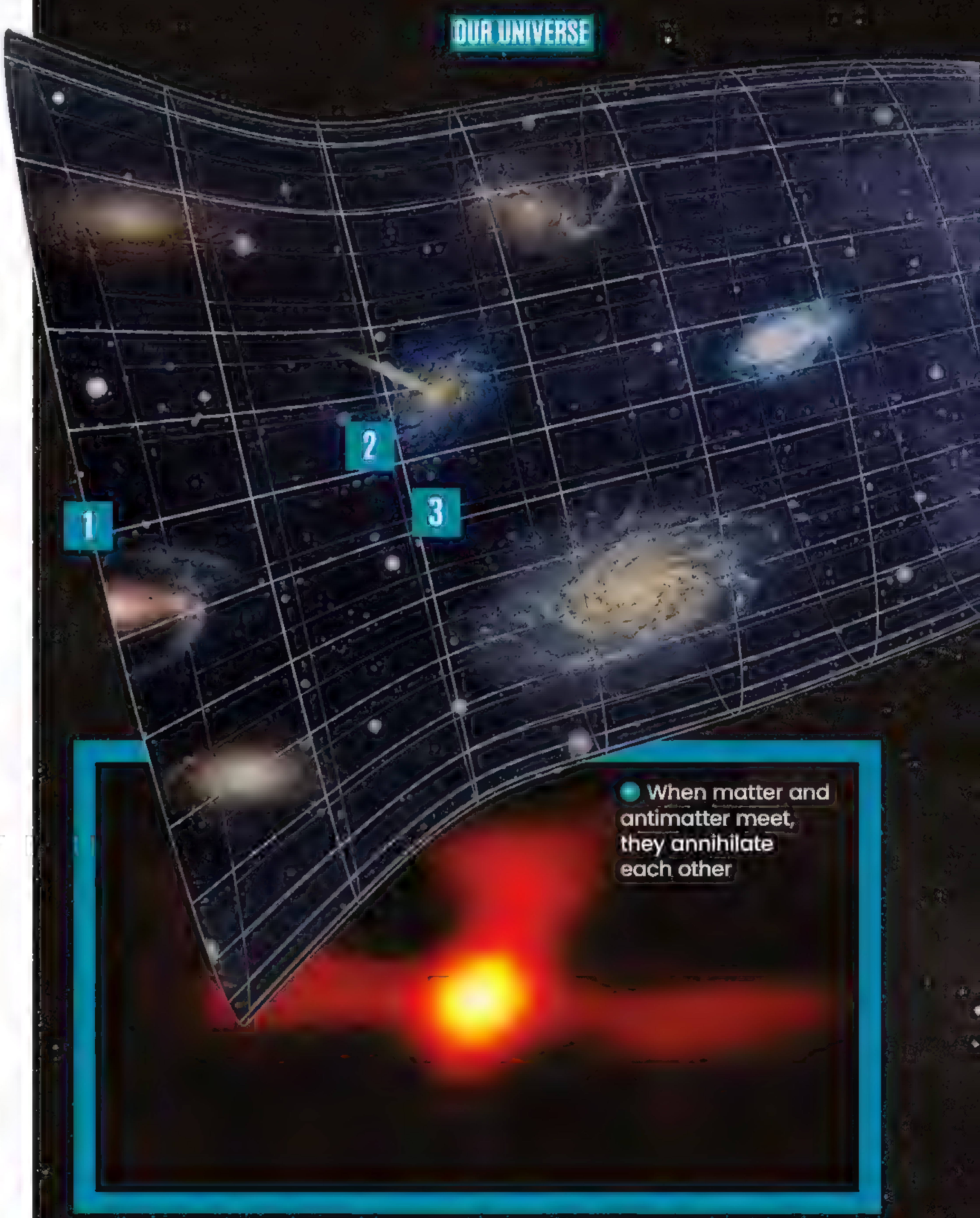
THE OTHER UNIVERSE

A symmetric universe conjures up an entire cosmos with equal and opposite properties to our own

1 Today's universe The present-day universe, with complex structures separated by large gaps in space but a broadly uniform structure on the very largest scales.

2 Looking back in time The speed of light means we see distant parts of space as they were long ago, turning the universe into a cosmic time machine.

3 Universe of matter Our universe is dominated by matter: Standard Model particles that include the positively charged proton and negatively charged electron.



When matter and antimatter meet, they annihilate each other

4 Cosmic fog
A dense fog of subatomic particles prevented radiation from travelling in straight lines in the very early universe.

5 Early era
Particle accelerators can collide particles with energies approaching those of the early universe.

6 First atoms
About 400,000 years after the Big Bang, subatomic particles coalesced into atoms, mostly of hydrogen.

7 Singularity
Space, time and all the energy in the universe erupted from a single superdense point called a singularity.

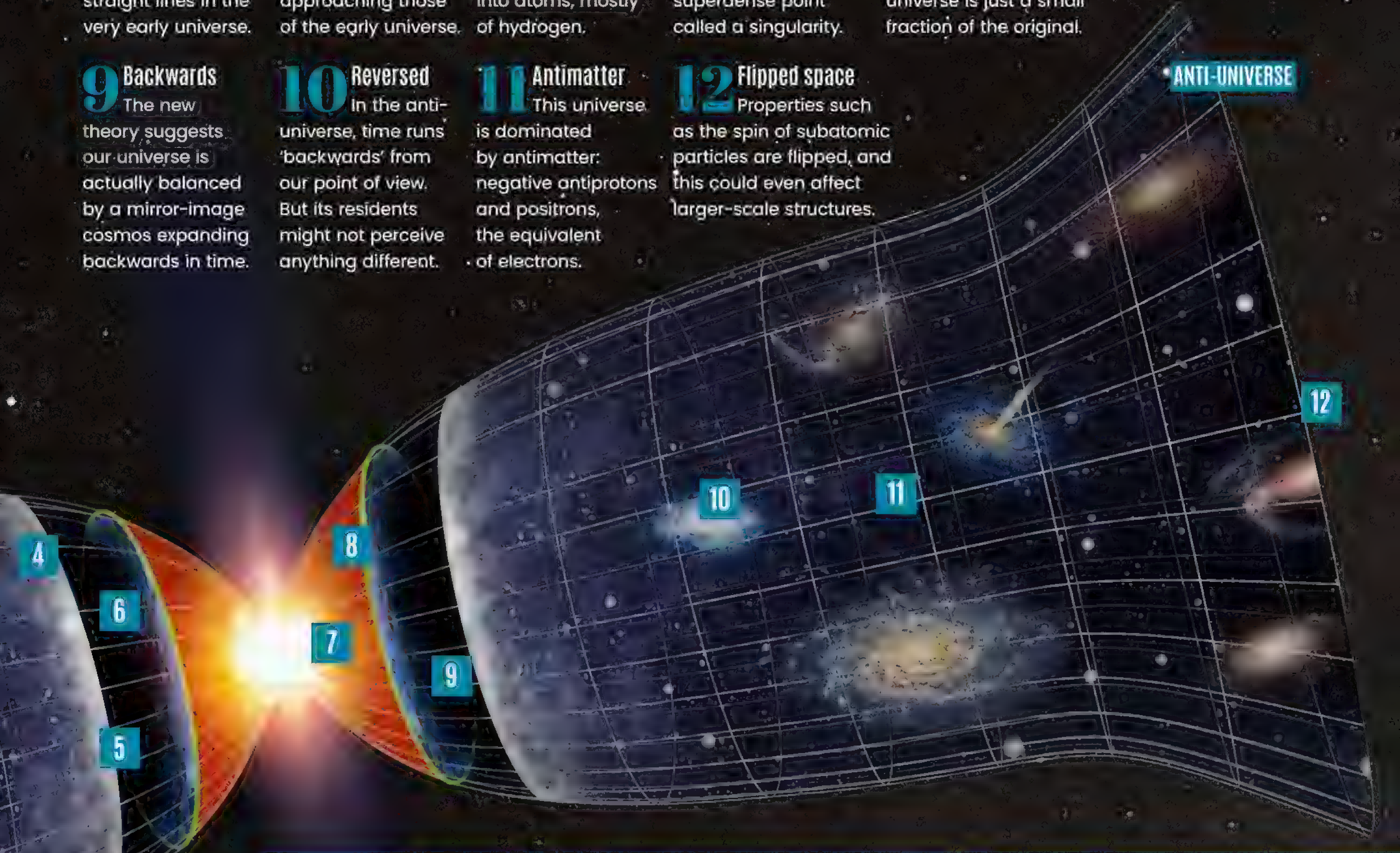
8 Into the unknown
The first fraction of a second remains beyond our reach, but one theory is that our universe is just a small fraction of the original.

9 Backwards
The new theory suggests our universe is actually balanced by a mirror-image cosmos expanding backwards in time.

10 Reversed
In the anti-universe, time runs 'backwards' from our point of view. But its residents might not perceive anything different.

11 Antimatter
This universe is dominated by antimatter: negative antiprotons and positrons, the equivalent of electrons.

12 Flipped space
Properties such as the spin of subatomic particles are flipped, and this could even affect larger-scale structures.



LIVING IN AN ANTI-UNIVERSE

If the anti-universe exists, what would conditions inside it be like?

What would an antimatter universe look like?
There's no reason a universe much like our own couldn't form out of the antimatter versions of particles in the Standard Model. Physicists have been making atoms of antihydrogen since the 1990s, and this would be the dominant component of the anti-universe, just as hydrogen is the dominant element in ours. One big question is whether gravity affects matter and antimatter in the same way – most think it should, but experiments to confirm this are only just becoming practical.

Could there be anti-life?
Assuming gravity pulls antimatter together in the same way as normal matter, the anti-universe should have its own stars and planets that could give rise to their own complex chemistry, and eventually life. In fact, a strict interpretation of CPT symmetry would imply that the anti-universe is a genuine mirror image of our own, with antimatter versions of Earth and its population.

How would time flow?
Although time in the anti-universe would run in the opposite direction from our point of view, its inhabitants wouldn't be aware of anything unusual. The laws of thermodynamics, which loosely define the 'arrow of time' and the direction in which things tend to break down into chaos, would flow in the opposite direction, and so would everything else. If we could observe the anti-universe from 'outside' we would see it as a strange place in which structure evolved backwards in time, but from inside things would appear just the same – from the point of view of an anti-cosmologist, our universe would be the one in which time flows backwards.

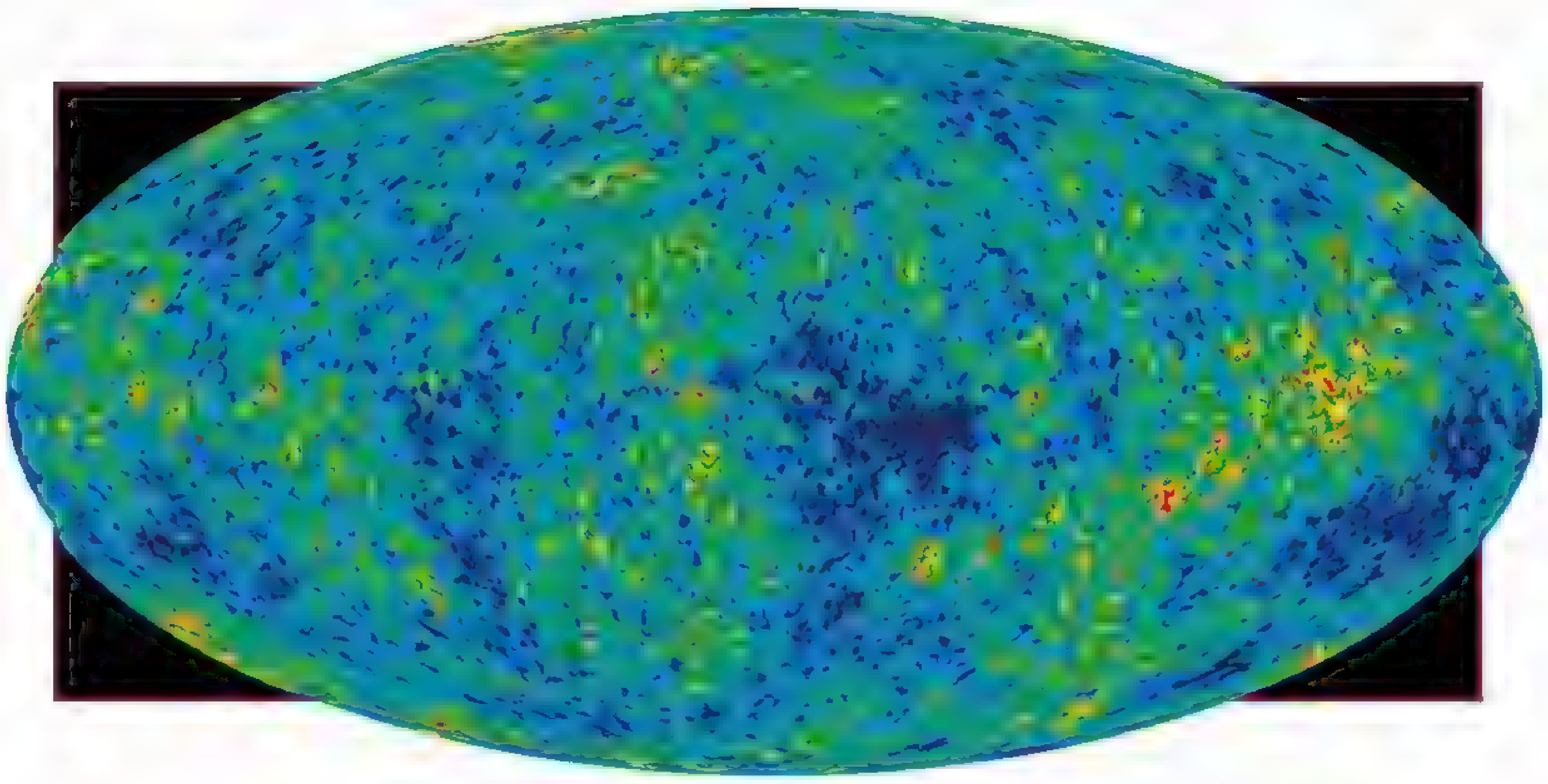
us – the universe and the Big Bang at its beginning are really in the CPT-symmetric state, but a present-day observer far away from the Big Bang defines a different state, so we should find these neutrinos being radiated from the Big Bang in much the same way as particles radiate from a black hole."

The theory allows Turok and Boyle to estimate the mass of the dark-matter neutrino at a billion times the mass of a proton. This enables them to calculate the energy of particles emitted if the neutrino occasionally disintegrates or decays into particles of more easily detected matter – but what if that doesn't actually happen? "We also predict other things that we can measure and which will be tested with future experiments," says Boyle. "We still have difficulty measuring the masses of the light neutrinos that we know about, and our theory predicts that the lightest of the light neutrinos will be exactly massless. Various experiments are going after that measurement, and cosmological measurements in particular are pushing the sum of the three light neutrino masses down towards its lowest possible limit." The KATRIN project in Germany is one example of scientists making great headway with this particular condundrum, although this phase is due to stop at the end of 2025.

"Another prediction is that there should be no primordial gravitational waves", continues Boyle. "There are competing models that predict whether such waves could be present."

Promising though Turok and Boyle's, theory is, it is still relatively new, and although it offers intriguing explanations for some unexplained aspects of the universe, there are others where it cannot yet match the long-established inflation model, as Boyle freely admits. "One very important thing we do not yet claim to explain is the 'power spectrum' of the primordial density perturbations. Another is why, if you ignore the perturbations, the very large-scale structure of the universe is both homogeneous and isotropic – in other words, it looks the same in every direction and it looks the same if you move through it in some direction in space. The original papers we put out just took that for granted, but we do have something in the works that we hope will give an explanation for this."

Perhaps the most appealing aspect of the theory is its simplicity – it doesn't require unseen dimensions beyond the familiar ones of space and time, and neither does it rest upon a host of new particles beyond those that are already known or suspected to exist in the Standard Model. "In that sense it gives a very minimal description of the cosmos," reflects Boyle. All it takes is an anti-universe.



Cosmic microwave background radiation offers the farthest and earliest view of our universe, about 400,000 years after the Big Bang

Giles Sparrow

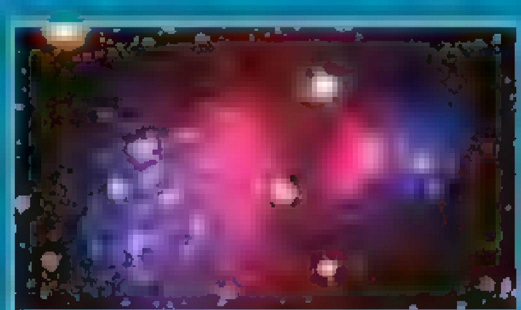
Space science writer

The author of over 20 books on popular science, Giles holds a degree in astronomy and is an editor specialising in science and technology.

EVIDENCE FOR A BACKWARDS UNIVERSE

No primordial waves

In some models of inflation, cosmologists predict that powerful space-time ripples called gravitational waves should have been produced (although others disagree). A CPT-symmetric universe would produce no such waves.

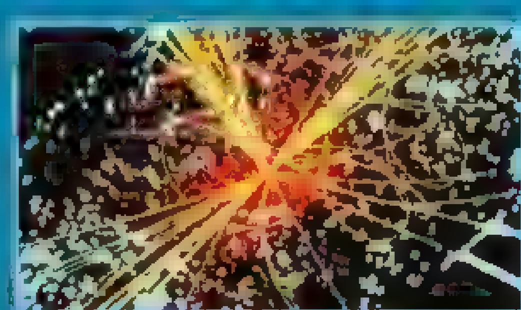


The dominance of matter

If the universe we see is all there is, then another question arises – why is it made of matter rather than an equal mix of matter and antimatter when the Big Bang should have created both in equal amounts?

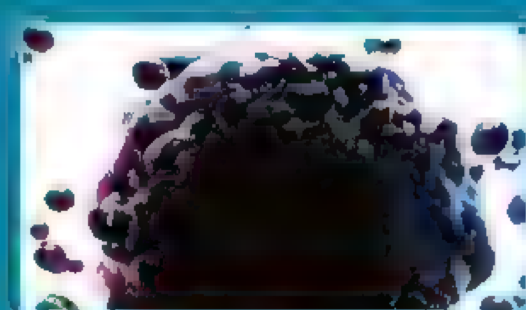
The arrow of time

Despite CPT symmetry, the universe as a whole shows a marked preference for time to flow in a single direction – for example, eggs smash if they are dropped, but never spontaneously reassemble themselves if the fragments are dropped again.



CPT symmetry

The laws of physics seem to obey a fundamental rule called CPT symmetry: if a particular subatomic process is possible, then a mirror-image process in which electric charges are flipped and coordinates of space and time are reversed can also happen.



Dark matter

Dark matter seems to account for 85 per cent of the mass in the universe. The CPT-symmetric theory suggests dark matter could be relatively simple particles called 'right-handed neutrinos', which are ruled out in more traditional views of the cosmos

HOW WE WOULD GET TO ANOTHER UNIVERSE

Travelling to another universe lies well beyond the limitations of current physics and technology, but how might we do it?

Time travel

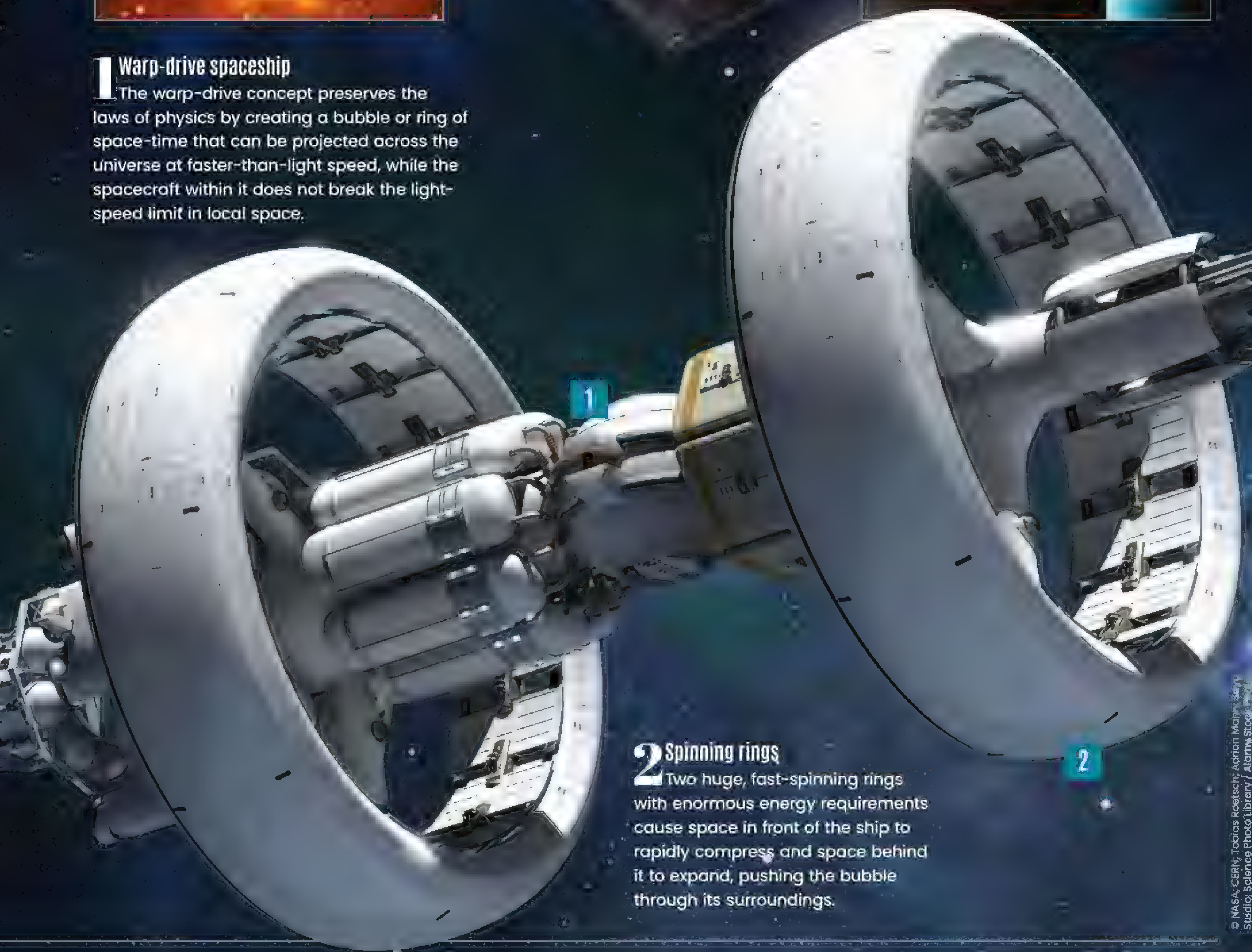
One way of reaching the CPT-symmetric anti-universe would require travelling backwards in time, past the Big Bang and surviving in a realm of antimatter without being instantly annihilated. Powerful magnetic fields can be used to keep matter and antimatter apart from each other.

Wormholes

These hypothetical shortcut passages through space and time look like black holes at either end, but lack the deadly singularity in the middle. Wormholes might exist naturally or be manufactured by advanced civilisations, but they would only be useful for hopping around 'our' universe – they could never link to the anti-universe.

Interstellar travel

Our universe extends far beyond the limits of what we can see, and may be effectively infinite. That would mean a multitude of other 'observable universes' beyond our own, theoretically reachable by faster-than-light interstellar travel. But again this wouldn't be a way of reaching the anti-universe.



1 Warp-drive spaceship

The warp-drive concept preserves the laws of physics by creating a bubble or ring of space-time that can be projected across the universe at faster-than-light speed, while the spacecraft within it does not break the light-speed limit in local space.

2 Spinning rings

Two huge, fast-spinning rings with enormous energy requirements cause space in front of the ship to rapidly compress and space behind it to expand, pushing the bubble through its surroundings.

ZOMBIE STARS

+10 OTHER TERRIFYING SPACE OBJECTS

Written by Laura Mears

Take a trip around the scariest stars, planets and galaxies lurking in the corners of our universe

Space has been an inspiration behind human mythology for thousands of years, and with a little help from technology, we are capturing some images that really bring these legends to life. However, far from being evidence of the supernatural at work, the spooky space images that we are about to show you are nothing out of the ordinary.

Humans can't help but try to find meaning in meaningless shapes, and the phenomenon even has a name – pareidolia. It is why we see faces in the clouds, religious icons in our food and constellations in the night sky.

The universe really is a dangerous place, where massive galaxies swallow up their neighbours and greedy stars feast on their close companions. But with the power of pareidolia, it also has witches and ghosts made from glowing gas, zombie stars and winking demons. The Sun has even transformed into a grinning pumpkin. Our universe has it all. Read on for our pick of the most terrifying space objects.

1 HELL PLANET

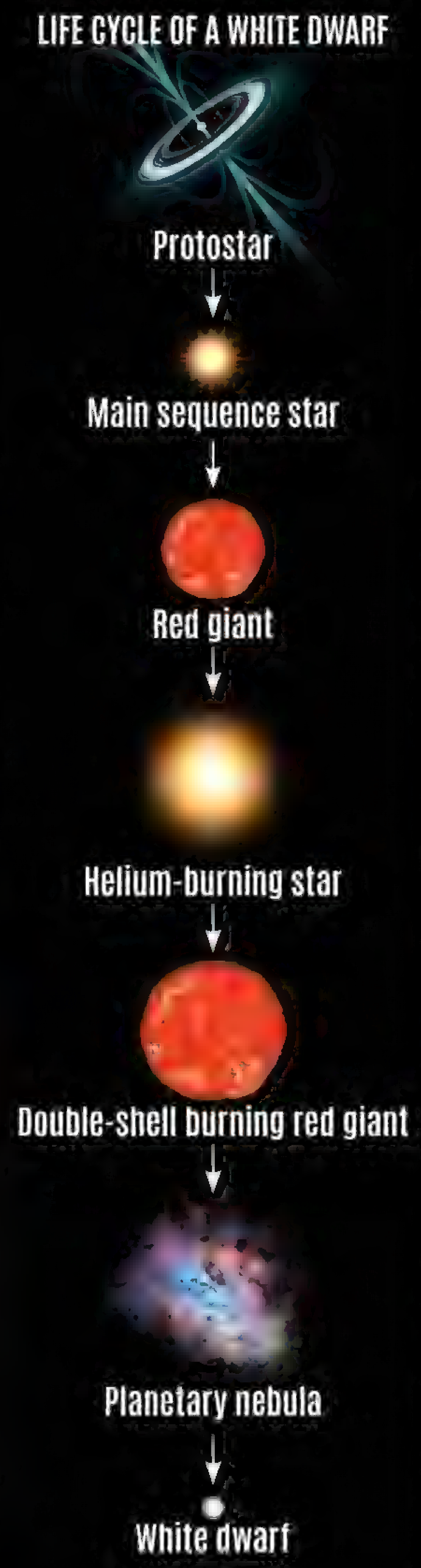
CoRoT-7 b is one of the most Earth-like planets ever discovered, but this alien world is no place for a human. Just over one-and-a-half times the size of our own planet, and almost five times the mass, CoRoT-7 b more closely resembles a depiction of hell than a second home. Its star, CoRoT-7, is younger than ours, and CoRoT-7 b orbits it at around 2.5 million kilometres (1.5 million miles) – 60 times closer than Earth is to the Sun. This journey takes just over 20 hours, and the planet skims so close that its surface melts under the daylight and the rocks boil away into space.

Scientists think CoRoT-7 b could once have been a gas giant with a mass similar to Saturn. It originally orbited around 50 per cent farther away from its star, but the searing heat stripped away the outer layers of gas. The planet is thought to have lost several Earth masses of material, and as it decreased in size, gravitational tides changed its orbit, bringing CoRoT-7 b even closer to the heat of its star.

2 LITTLE GHOST NEBULA

The wispy halo of the Little Ghost Nebula surrounds a white dwarf star in the constellation of Ophiuchus. The white dwarf emits high-energy ultraviolet (UV) radiation, which slams into the clouds of dust and gas surrounding it, exciting the particles and causing them to glow. The main ring is made from a combination of ionised hydrogen, oxygen and nitrogen, and each emits different wavelengths of radiation. The Little Ghost is a planetary nebula, created as the star at its centre ran out of fuel. In fact, it's a ghostly premonition of the fate of our Solar System.

Once similar in size to our Sun, the star at the heart of the Little Ghost Nebula ran out of hydrogen fuel, and as it switched to using helium, temperatures soared. The intense heat caused the star to swell, forming a red giant. The red giant tore through its supply of helium quickly, generating carbon in the process. The heavy ash crunched down towards the core of the star, and as it tumbled inwards, some ignited, producing shocks that jettisoned the outer layers of its atmosphere into space. The dust and gas that spilled out formed the Little Ghost Nebula.



Two UV wavelengths are coloured gold and yellow, producing an eerie pumpkin-like Sun

3 JACK-O'-LANTERN SUN

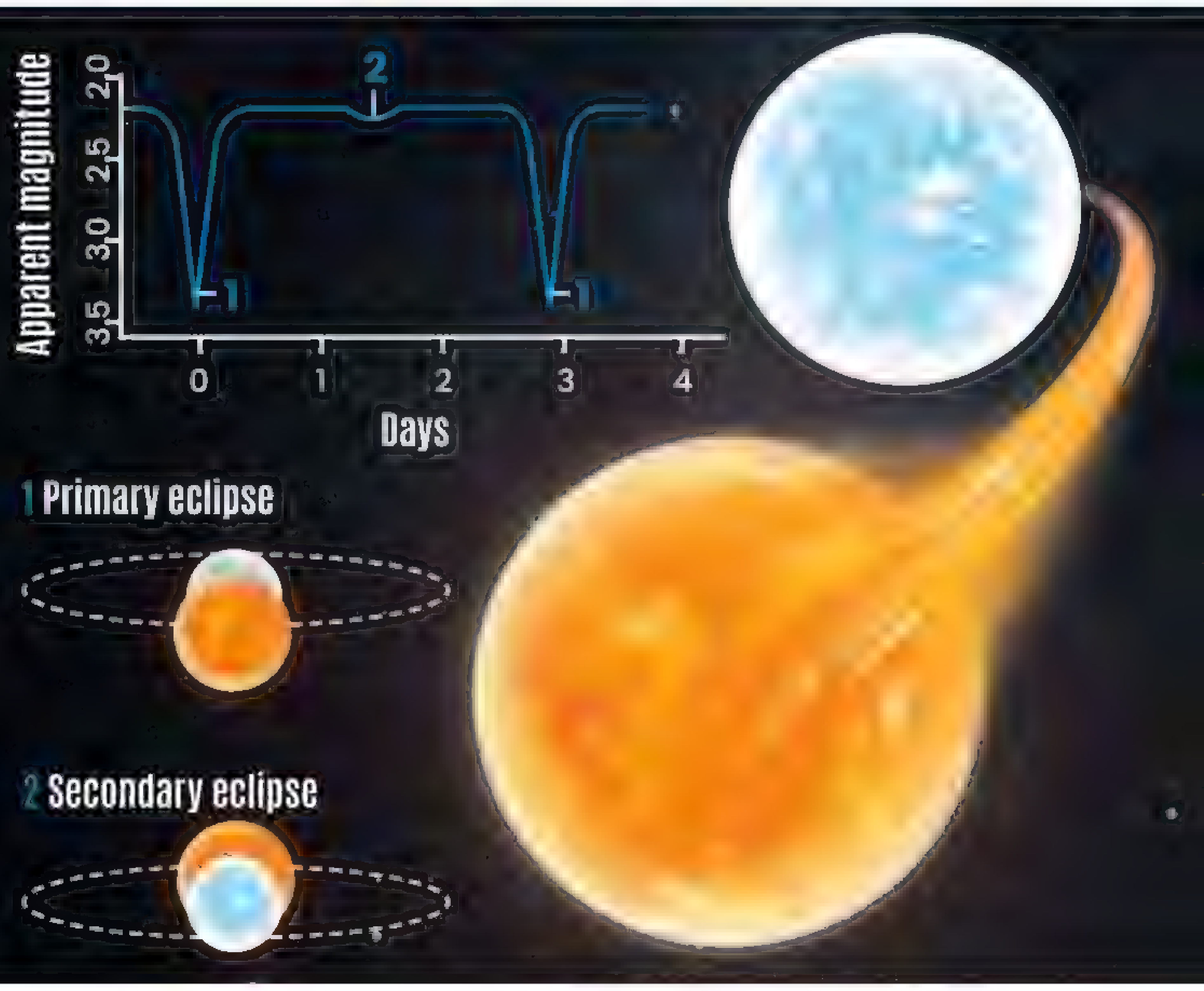
NASA's Solar Dynamics Observatory is studying the Sun's activity. In October 2014, it watched as our star put on a Halloween mask. The temperature and pressure at the core of the Sun are so intense that atoms slam into one another and fuse, releasing huge amounts of energy. This powers the movement of streams of plasma – gas so hot that it has broken apart to form free charged particles. The movement of these charged particles transforms the Sun into a powerful magnet.

The bright areas in this picture represent extreme ultraviolet light released in areas of intense magnetic pressure. The magnetic field lines inside the Sun are always moving, and sometimes areas of extreme magnetic pressure build up. This is similar to trying to force the north poles of two bar magnets together, but on a massive scale. Some of these regions of pressure burst through the surface of the Sun, taking streaks of plasma with them and forming visible sunspots.

5 DEMON STAR

In Arabic, 'al Ghul' means 'the demon', and this sinister star lives up to its name in constellation mythology. It makes up the head of the ancient Greek snake-haired monster Medusa in the constellation of Perseus, and every few days its light dims dramatically before returning to normal, as if Algol were winking at the Earth.

However, this gesture is far less sinister than it seems. It happens because Algol is actually a three-star system, and two of the stars are orbiting extremely close together. From Earth we see their orbits edge-on, so at regular intervals, one star passes in front of the other, blocking our view. Most of the light we attribute to Algol is produced by a bright, blue star, with a small proportion contributed by a dimmer red-yellow star. When the blue star passes in front of the yellow star, we barely notice the difference, but when the yellow star blocks our view of the blue star, the light changes dramatically.



4 ZOMBIE STARS

Supernovae are some of the largest explosions in space, and evidence suggests some might leave behind zombie stars. Type Ia supernovae happen in binary star systems where a white dwarf star is stealing hydrogen gas from its companion. As more and more matter accumulates, the white dwarf can become unstable, leading to a dramatic explosion that completely destroys the star.

Type II supernovae are more dramatic and are caused by the death of a massive star. As it runs out of fuel, the star crunches in on itself, releasing vast quantities of energy and leaving behind a dense neutron star, or even a black hole. It was thought that exploding stars were always destroyed by the blast, but in 2012 scientists revealed a new type of survivable supernova. Like Type Ia supernovae, Type Iax supernovae are the result of white dwarf stars in binary systems, but this time they are stealing helium gas instead of hydrogen. The result is a much smaller explosion, allowing the damaged star to reappear once the dust has settled, like a zombie raised from the dead.

In 2014, NASA's Hubble Space Telescope captured a picture of one of these dim supernovae. The Intermediate Palomar Transient Factory wide-field camera survey in California also captured what was first thought to be an exploding star in 2015, before realising that instead of dying, it kept going.

6 FRANKEN NEBULA

Within this bright stellar nursery, hot, blue stars are constantly emerging from the clouds of dust and gas, and their energetic emissions are sculpting a scary silhouette. NGC 2467 is a young open star cluster sometimes likened to Frankenstein's monster or a deathly skull, and in this image, captured by the European Southern Observatory, it's easy to see why.

NGC 2467 is just a few million years old, and is shrouded in large clouds of dust and gas. It is the birthplace of hundreds of new stars, and the energy that they release has been sculpting the nebula. The monster's lower eye is a star cluster known as Haffner 19, still encased in a cloud of partially ionised gas, and its right eye is a star called HD 64455. The nose is an elongated open star cluster known as Haffner 18, containing around 50 massive young stars, and the lower jaw is being chiselled by a bright double or multiple star called HD 64315. Over time, as these hot, young stars continue to sculpt the clouds of the nebula, its eerie outline will change, but for now, it's truly a stellar monster.

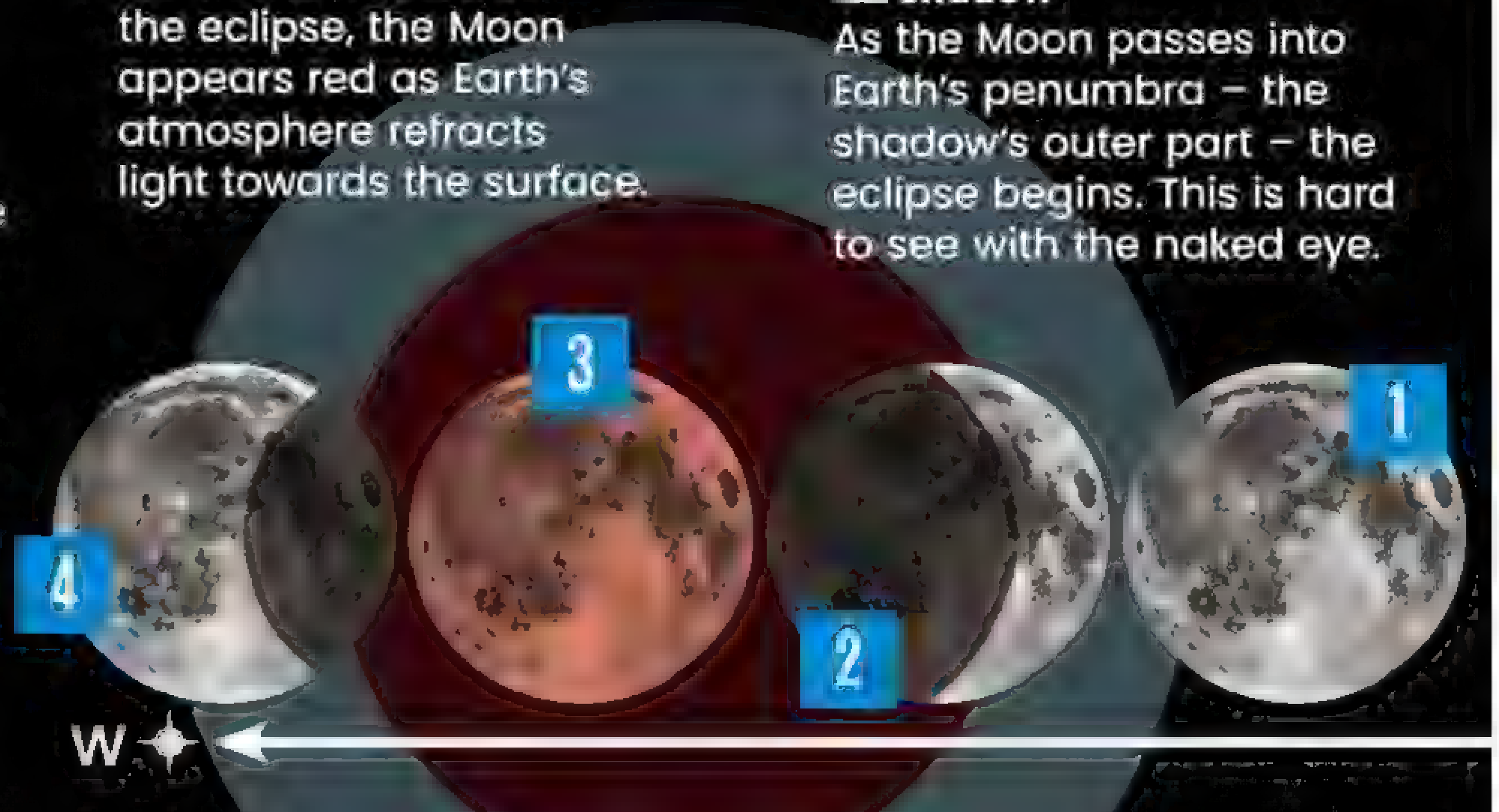
7 BLOOD MOON

During a total lunar eclipse, when the shadow of Earth falls directly over the Moon, the lunar surface can take on a reddish hue. To some people, this is the warning sign of an impending apocalypse. When Earth comes between the Sun and the Moon, some sunlight still strikes the surface, but along the way it has to pass through Earth's atmosphere. As it collides with the gas and dust particles, some of the light is scattered. Shorter wavelengths at the blue end of the spectrum scatter more, which is why the sky appears blue, and longer wavelengths at the red end of the spectrum scatter less. Some of this light is bent towards the Moon, hitting the surface and casting a blood-like glow – the exact shade varies depending on the conditions in the atmosphere at the time.

A blood-red Moon is referenced in the Bible, and over time mythology has built up around this strange phenomenon – a few people believe that four blood Moons in a row will signal the end of the world.

3 Total eclipse In the middle of the eclipse, the Moon appears red as Earth's atmosphere refracts light towards the surface.

1 Moon enters Earth's shadow As the Moon passes into Earth's penumbra – the shadow's outer part – the eclipse begins. This is hard to see with the naked eye.



4 Moon exits Earth's shadow As the Moon exits Earth's shadow, the colour of the surface returns to normal.

2 Moon enters the umbra The eclipse becomes visible as the Moon enters Earth's shadow, or umbra.

8 SPACE'S EVIL EYE

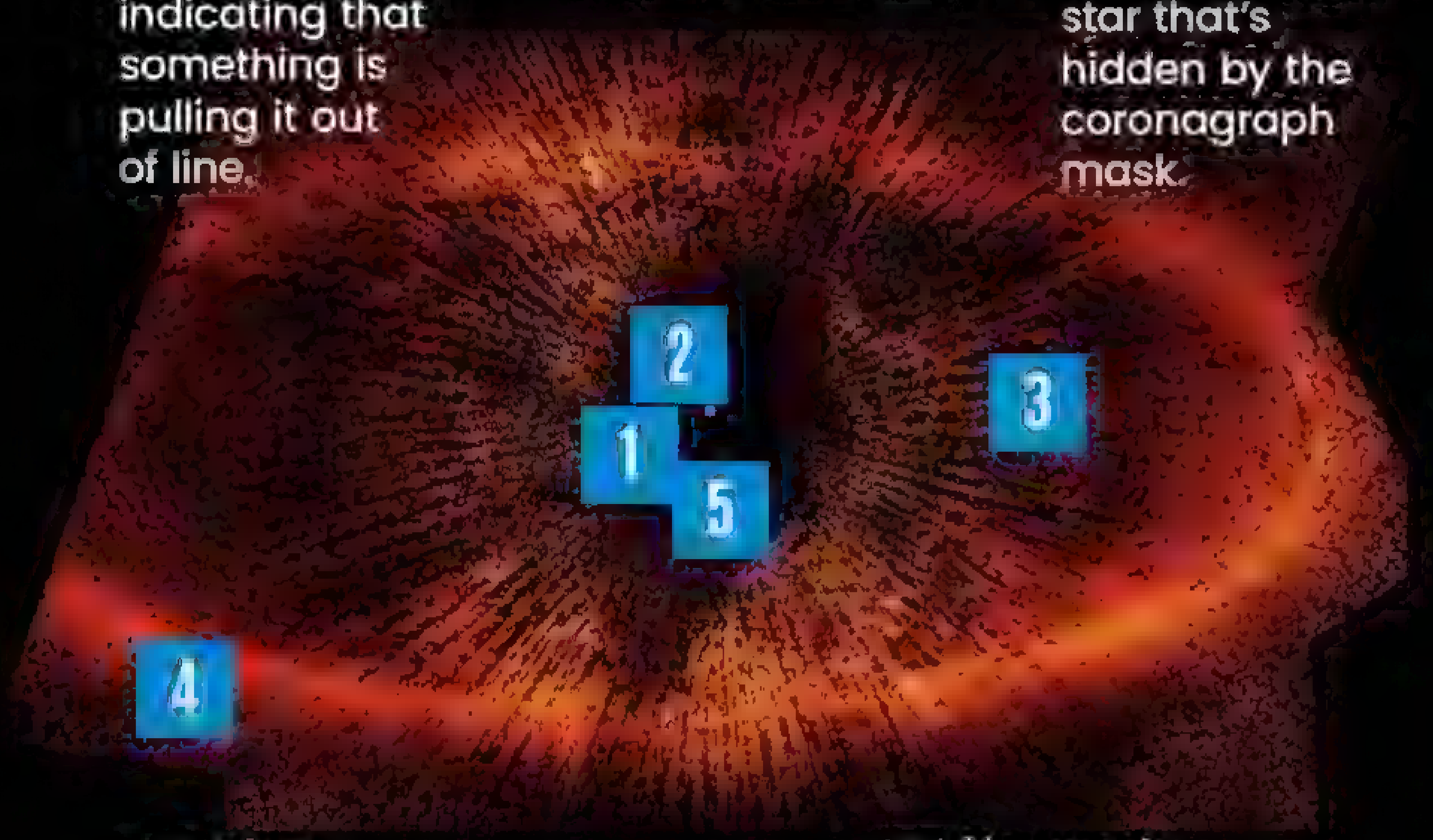
Fomalhaut is a hot white star about twice the mass of the Sun, but take a look at this image from the Hubble Space Telescope and you might think you're looking straight into the Eye of Sauron from *The Lord of the Rings*. Fomalhaut is surrounded by several discs of frozen dust, which are warmed by the star and emit a faint glow of infrared radiation. When the much brighter light of the white star is blocked out, the faint light reveals the stunning detail of the eye-shaped debris.

The disc extends out to about five times the distance between Pluto and the Sun, and the patterns and distortion indicate that there are planets in the dust. By comparing photos taken at different times, researchers pinpointed the location of the first in 2008.

1 Ring centre The centre of the ring is 2.2 billion kilometres (1.4 billion miles) from the star, indicating that something is pulling it out of line.

2 Star The star at the centre of the system is bright and young, over two times the mass of the Sun.

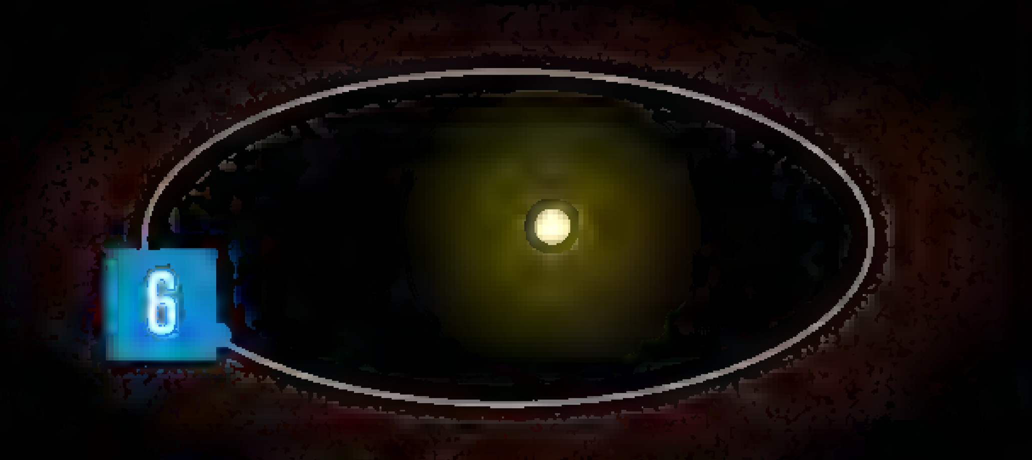
3 Scattered light The 'iris' of the evil eye is actually scattered light from the bright star that's hidden by the coronagraph mask.



4 Ring The debris ring makes up the outline of the eye. Hubble has spotted a dust-covered planet orbiting just inside.

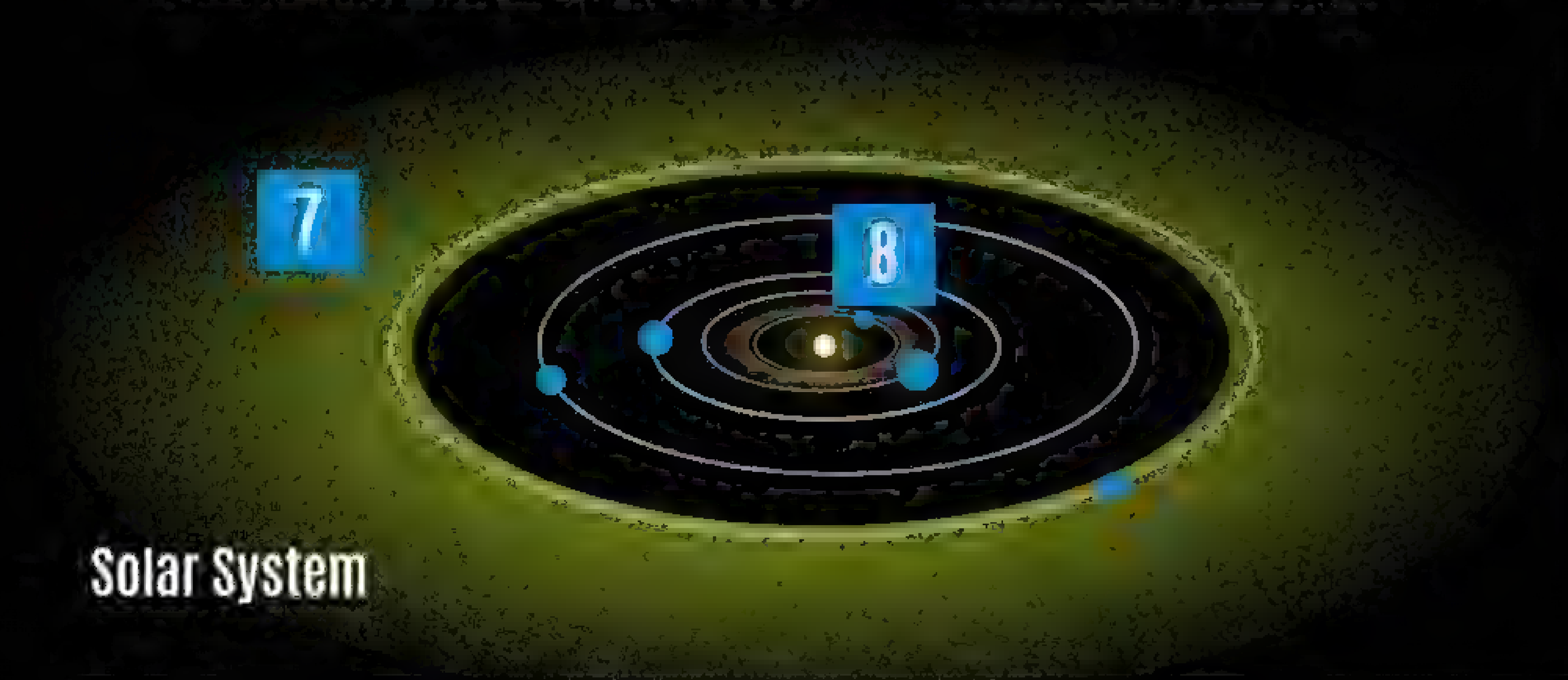
5 Star mask Light from the star has been blocked by a coronagraph, allowing the structure of the rings to be examined.

6 Exoplanet Fomalhaut A planet has been spotted orbiting Fomalhaut that is just inside the ring of dust.



7 Kuiper Belt The debris ring has a radius more than 130 astronomical units. The Kuiper Belt is only around 50 astronomical units.

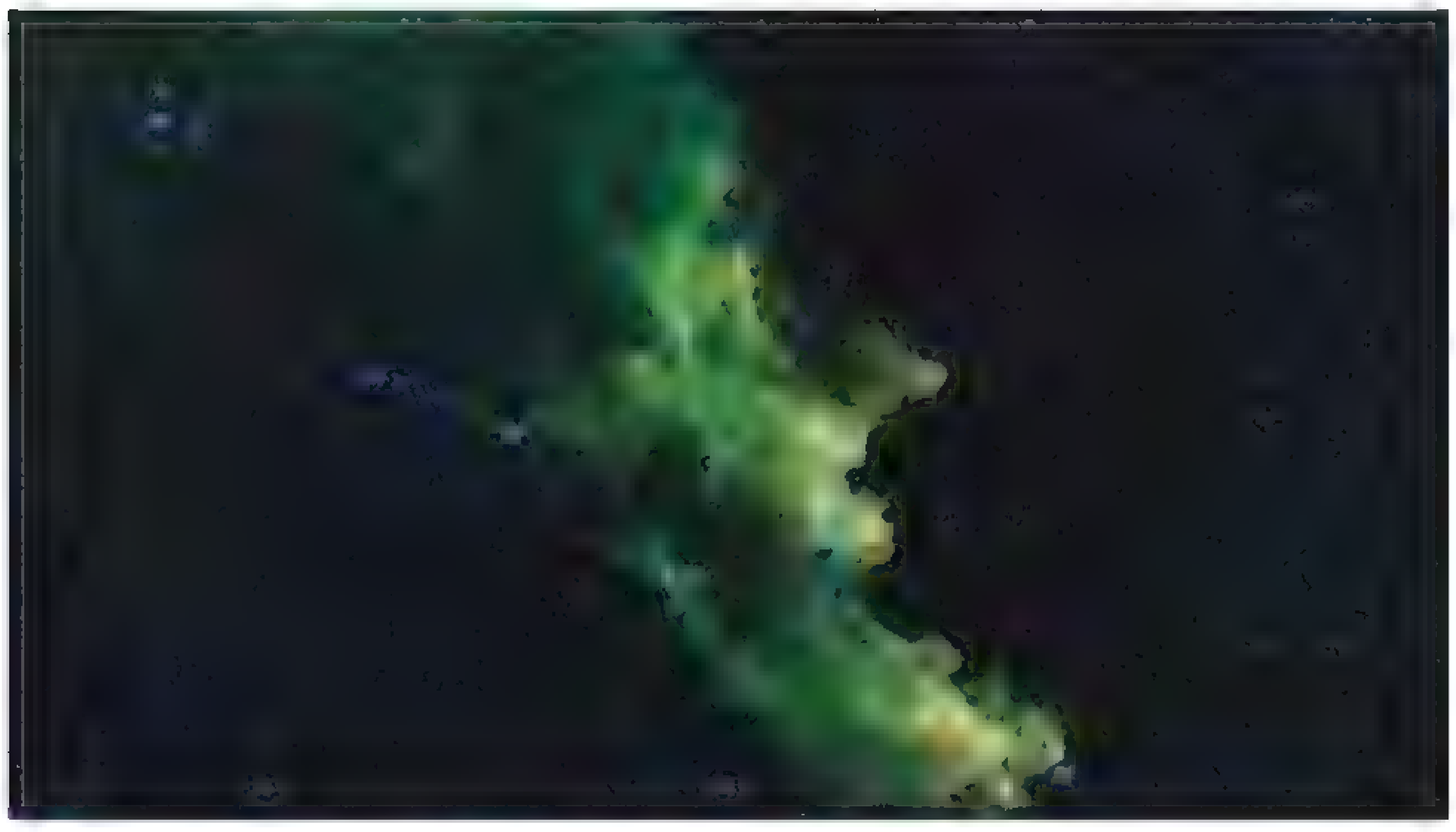
8 The asteroid belt The asteroid belt is smaller still, beginning at around two astronomical units from the Sun.



9 STELLAR VAMPIRES

Many of the stars in our galaxy are part of 'binary systems', sharing their space with a stellar companion. The two orbit around a shared point known as their common centre of mass, and as they age they often come a bit too close for comfort. When a star starts to run out of hydrogen fuel, it swells to become a red giant. The gases at the edges can no longer be contained by gravity and they start to spill out into space. If two stars are close enough, the red giant's neighbour will start to suck up the excess. In many binary pairs, one star is feeding on its partner, using the gas to fuel its own internal fusion reactor. These vampire stars are effectively stealing the lifeblood of their neighbours.

A red giant can get so big that it engulfs its companion. Rather than feeding on the gas spilling from the surface, this strange vampire orbits inside the expanded atmosphere.



10 WITCH HEAD NEBULA

This wispy outline, with its hooked nose and curved chin, bears a striking resemblance to the profile of a traditional fairy tale villain. It is known as the Witch Head Nebula or IC 2118.

The Witch Head Nebula is a reflection nebula, so it does not produce any light of its own, but it is found to the west of the constellation of Orion, next to the blue supergiant star Rigel. Rigel is one of the brightest objects in the night sky, between 40,000 and 100,000 times more luminous than the Sun. Even though it's over 40 light years from the nebula, the blue light that Rigel pours out into space illuminates the spooky silhouette of the Witch Head Nebula. It doesn't provide enough energy to ionise the gas and make it glow, but the light scatters as it passes through. The dust that comprises the nebula is able to scatter blue light more easily than it is able to scatter red, and as a result, Rigel's blue shade is intensified.

11 CANNIBAL GALAXIES

Massive galaxies grow by swallowing up the competition. Some examples are dramatic – like the famous Antennae Galaxies, which are in the process of merging right before our eyes – but even galaxies like our own have a cannibalistic past. Andromeda is a spiral galaxy very similar to the Milky Way. Most of its stars are arranged into a flat disc, and the rest circle the galactic centre in a halo. Within this halo, scientists noticed a stream of debris containing a group of metal-rich stars moving in the same direction.

These stars started life in another galaxy. They orbit the galactic centre, but they still have some memory of the direction they were travelling in before their galaxy was swallowed up, so they continue to move as a group. Andromeda was thought to be heading for another galactic feast, this time on a collision course with the Milky Way, and that we were due to merge in about 4.5 billion years. However, a 2025 study found that the collision may happen much later (about 10 billion years), or the galaxies might miss each other completely.

STARQUAKES

STARS ARE PLAYING A COSMIC CONCERTO THAT CAN REVEAL THE DEEP SECRETS OF THEIR INTERIORS

Reported by Robert Lea

The Sun may appear to be a stable and monolithic body sitting at the heart of the Solar System, but that isn't the case. Our star is rocking with 'starquakes' that have become an area of intense study for solar physicists. Beneath the Sun's surface is a roiling and violent sea of plasma that transfers energy from its core, where it's generated by the nuclear fusion of hydrogen to helium, to the Sun's surface – the photosphere – where it can be radiated out to rain sunlight down on Earth and the other planets. This process causes our star to shake, a phenomenon generally referred to as a starquake. Though only the surface of the Sun is visible to us, humanity has learned to deduce what lies beneath using these starquakes, just as seismic waves from earthquakes have been used to decode the interior of our planet. Now, this practice is being used to understand the interiors of more distant stars of all shapes, sizes and ages.

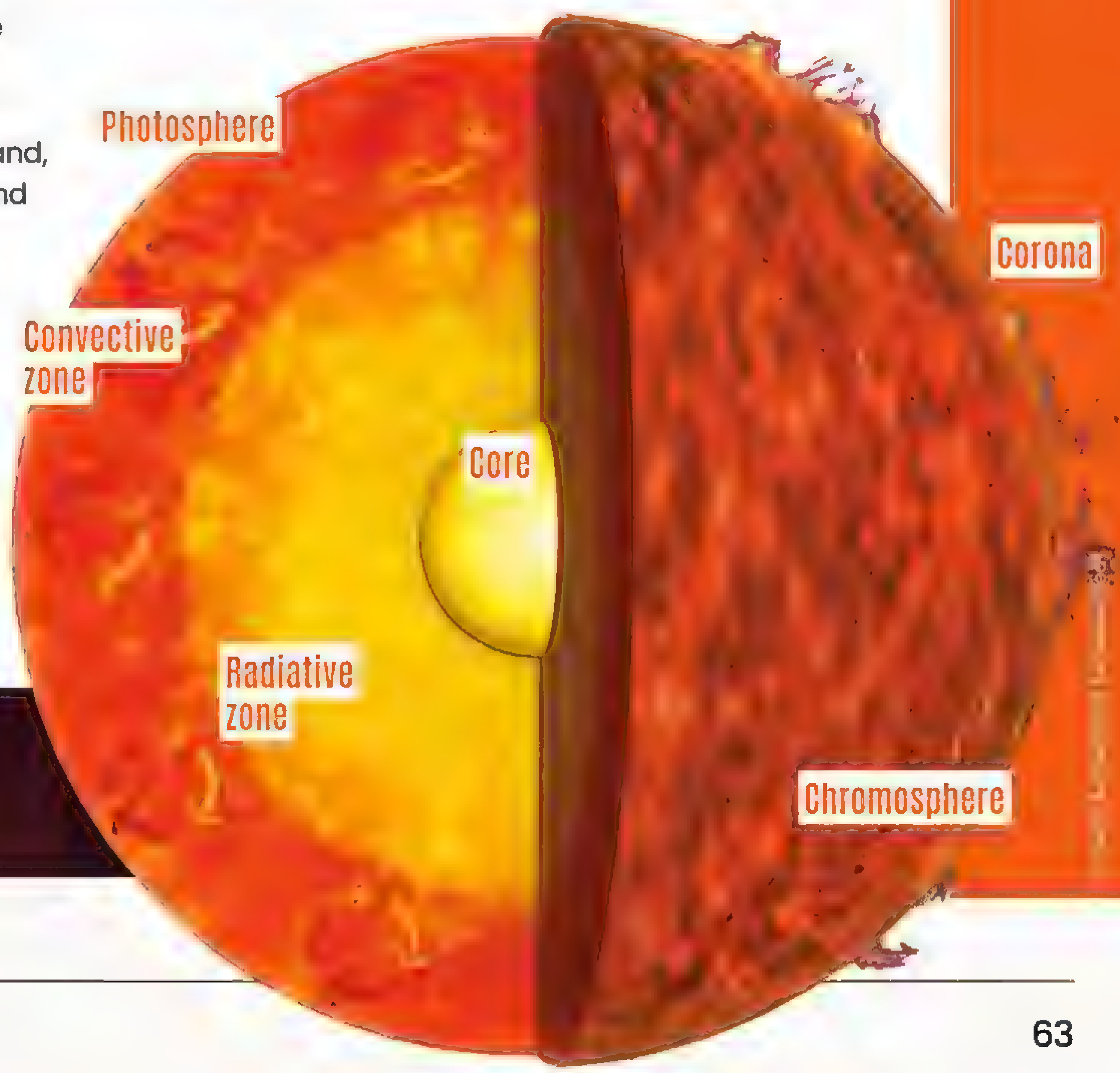
Though the name starquakes is reminiscent of earthquakes because stars are essentially superheated balls of gas, the causes of the two phenomena are very different. "I know it's a good way of catching people's attention to call them starquakes, and there are some analogies with earthquakes, but we generally talk about starquakes as the oscillations of stars," University of Toulouse scientist Sébastien Deheuvels told **All About Space** magazine. "An earthquake is something that very locally pushes the Earth to oscillate, but what we see for a star is the whole star oscillating, not just a part of it. So perhaps the most common analogy that we make is with musical instruments – when you pluck a guitar string, the whole string of the guitar oscillates."

On our planet, earthquakes are caused by sudden movements along faults within the Earth that release stored-up elastic energy as seismic waves. These waves propagate through the Earth and cause the ground surface to shake. Starquakes, on the other hand, happen because the Sun gently vibrates due to sound waves trapped in its interior. These sound waves are produced by fluctuations in pressure in the turbulent convective motions of the Sun's interior, and they rise outward, reflecting off the surface of our star. This trapped sound is excited when hot blobs of superheated gas called plasma rise on convective currents to the surface of the Sun, while plasma that has previously made this journey cools and falls through these so-called convective zones.

The trapped sound waves set the Sun vibrating in millions of single sound pitches, or 'modes', and since this is produced by pressure, these modes of vibration are called p-modes. "What we give as an example is usually boiling water, which generates convection, with hot water rising and then falling when it cools," Deheuvels says. "You have these big movements in the external part of the Sun, equal to about 30 per cent of its radius, which is convective and generates these motions. When these motions get near the Sun's surface it can excite the oscillation modes. That's what causes the oscillations in the Sun."

IF THE SUN WERE A TRUMPET

Campante says that though the frequencies of the starquakes the Sun experiences aren't audible to humans, this could be changed if we sped up the three millihertz signal by about 100,000 times. Then we could create a 300 hertz signal – or 300 oscillations per second – which would be well within our hearing range. "Different musical instruments have distinct and recognisable pitches. For fun, let us associate the Sun with a trumpet," Campante explains. He says smaller stars would have higher pitch overtones, so if the Sun is a trumpet, then smaller stars like red dwarfs would be a higher pitched instrument, like a cornet. The converse is also true. Larger stars than the Sun experience starquakes with lower pitch overtones. If the Sun were a trumpet, then a massive star would be a tuba.



Sound waves need a medium to propagate through, which means the vacuum of space stops these stellar sounds from propagating outwards to planets like Earth. This means stars like the Sun are putting on a cosmic orchestra that isn't possible to hear. But the vibrations of these stellar instruments can be seen, and thus the concert they play can be decoded. This is no mean feat, however. These oscillations of stellar surfaces are tiny. For the Sun, they amount to oscillations of a few tens of centimetres per second. They can be determined only thanks to tiny amounts of redshift and blueshift in light from the Sun as regions of its surface rise and fall. The signal this makes up is equivalent to about a millionth of the energy flux of the Sun. These signals are strongest near the centre of the disc of the Sun and weakest near the edge of our star. This indicates that starquake motions are primarily inward and outward, or 'radial', almost like the Sun is breathing out and in.

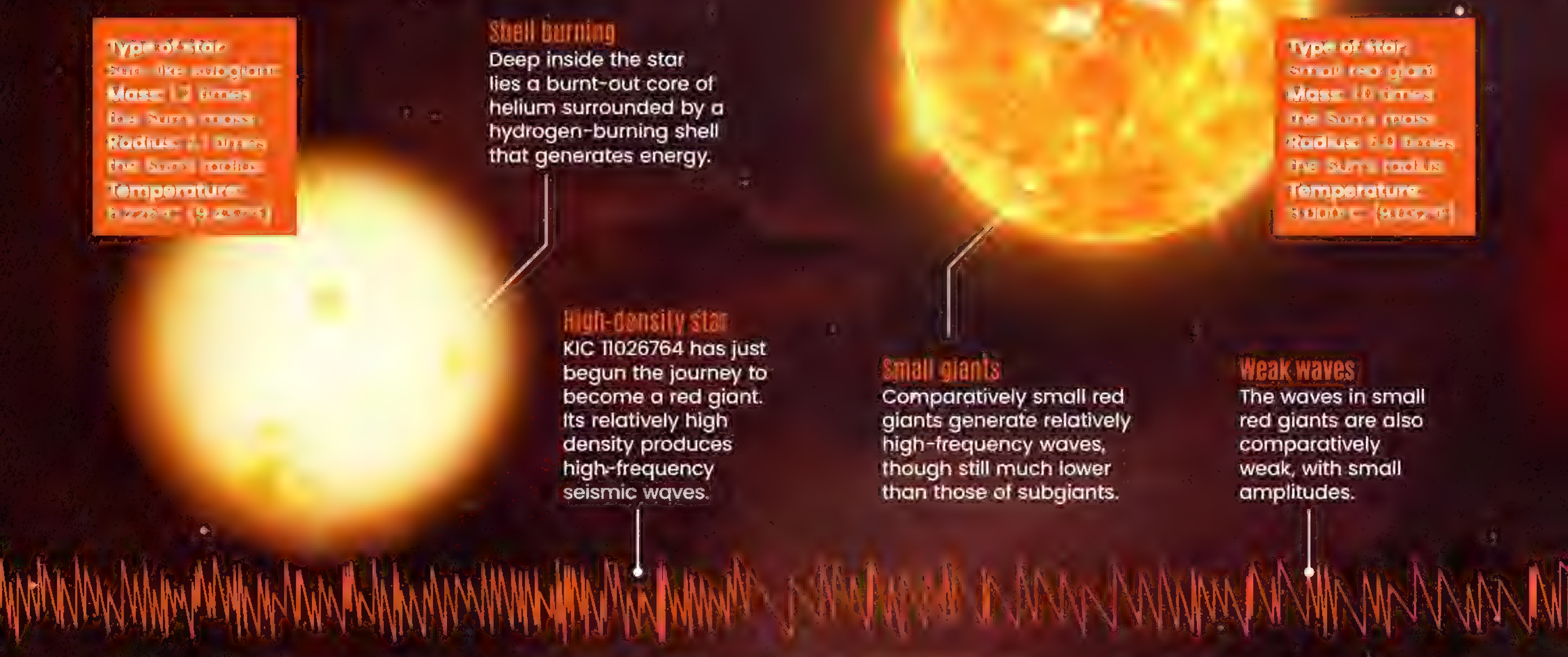
"The trapped sound waves make a star resonate, just like a musical instrument," assistant researcher at the Instituto de Astrofísica e Ciências do Espaço, Tiago Campante, told **All About Space** magazine. "Take the case of the Sun. The dominant modes of oscillation in the Sun have periods of about five minutes or, equivalently, frequencies of three millihertz." These frequencies are much too low to be audible to us with our hearing range of 20 hertz to 20 kilohertz, so to find out how the Sun 'sounds' thanks to starquakes, astroseismologists like Campante and Deheuvels take solar data and speed it up around 100,000 times, thus effectively converting the three millihertz signal into a 300 hertz signal that's within our audible range.

"The first detections of oscillations in the Sun date back to the 1960s and paved the way for the development of helioseismology, the study of the Sun's interior by the observation and analysis of oscillations at its surface," Campante says. "Through helioseismology, the Sun fulfils the role of a Rosetta Stone for astrophysics. Helioseismology allows us to study the Sun in great detail, and through this we can inform our understanding of the life histories of the Sun and other stars. The Sun is a single star at a specific evolutionary state, and it's further structurally simple if compared to

> "There are some analogies with earthquakes, but we generally talk about starquakes as the oscillations of stars"
> **Sébastien Deheuvels**

STELLAR CONCERT

Thanks to data from Kepler and other missions, it's becoming clear that all stars have their own oscillations, like instruments in an orchestra



THE SOUND OF STARS

A star's internal structure affects the pattern of oscillations seen at its surface

1 f-mode waves
Surface gravity waves are created at the surface and move across the star like waves on the ocean.

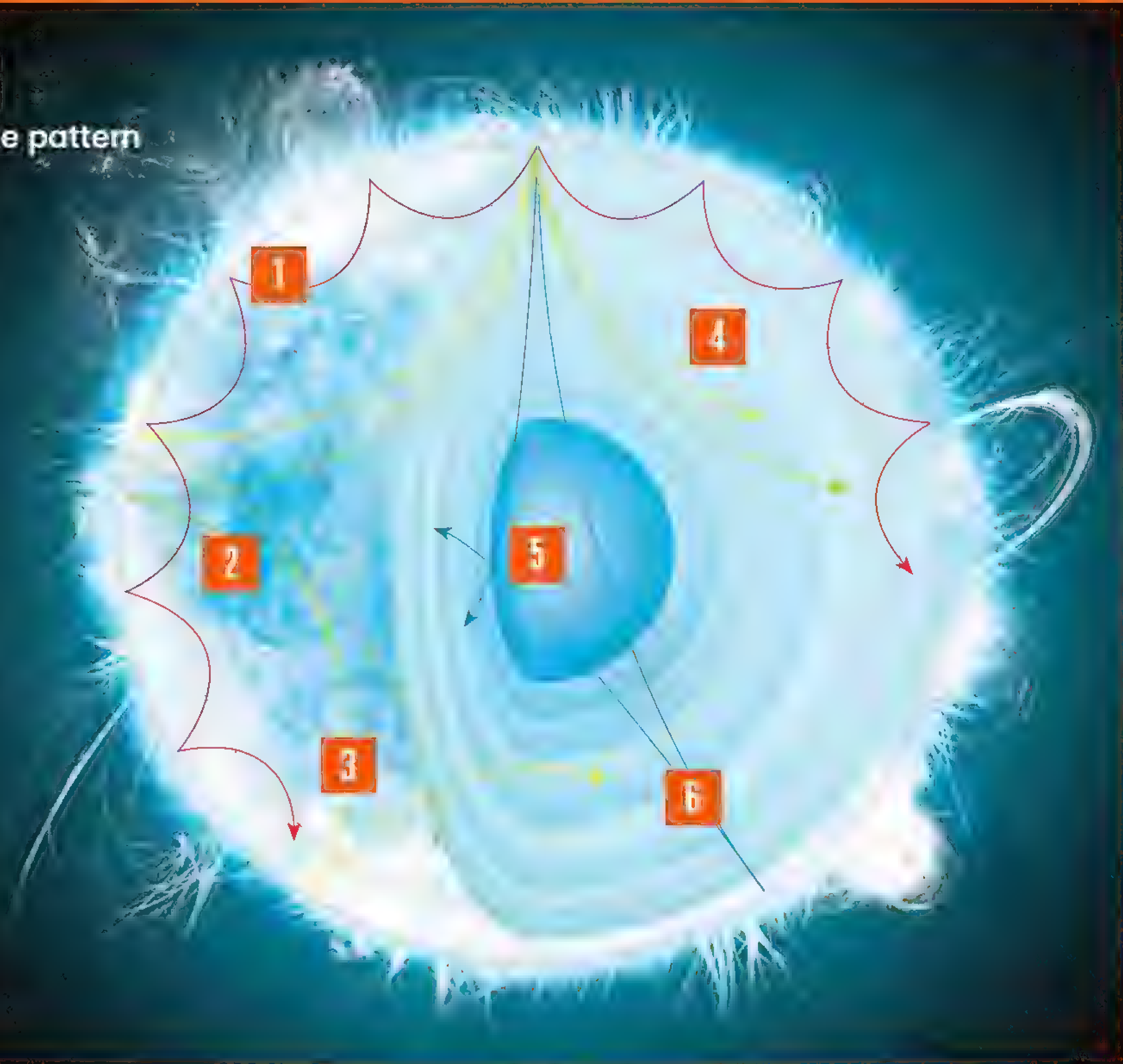
2 p-mode waves
Pressure waves are most similar to sound waves, generated by local pressure changes inside the star.

3 g-mode waves
Gravity waves are generated where gravity counteracts the internal buoyancy of rising gas.

4 Layering
The passage from one internal layer of a star to another with different properties can deflect waves, or even reflect them completely.

5 Core chemistry
The speed at which waves travel straight through the core reveal its composition and likely age.

6 Rotation
The rotation of the core influences waves passing through or near it, creating patterns that can reveal its rate of spin.



Type of star: Large red giant
Mass: 5.0 times the Sun's mass
Radius: 20 times the Sun's radius
Temperature: 4,000°C (7,232°F)

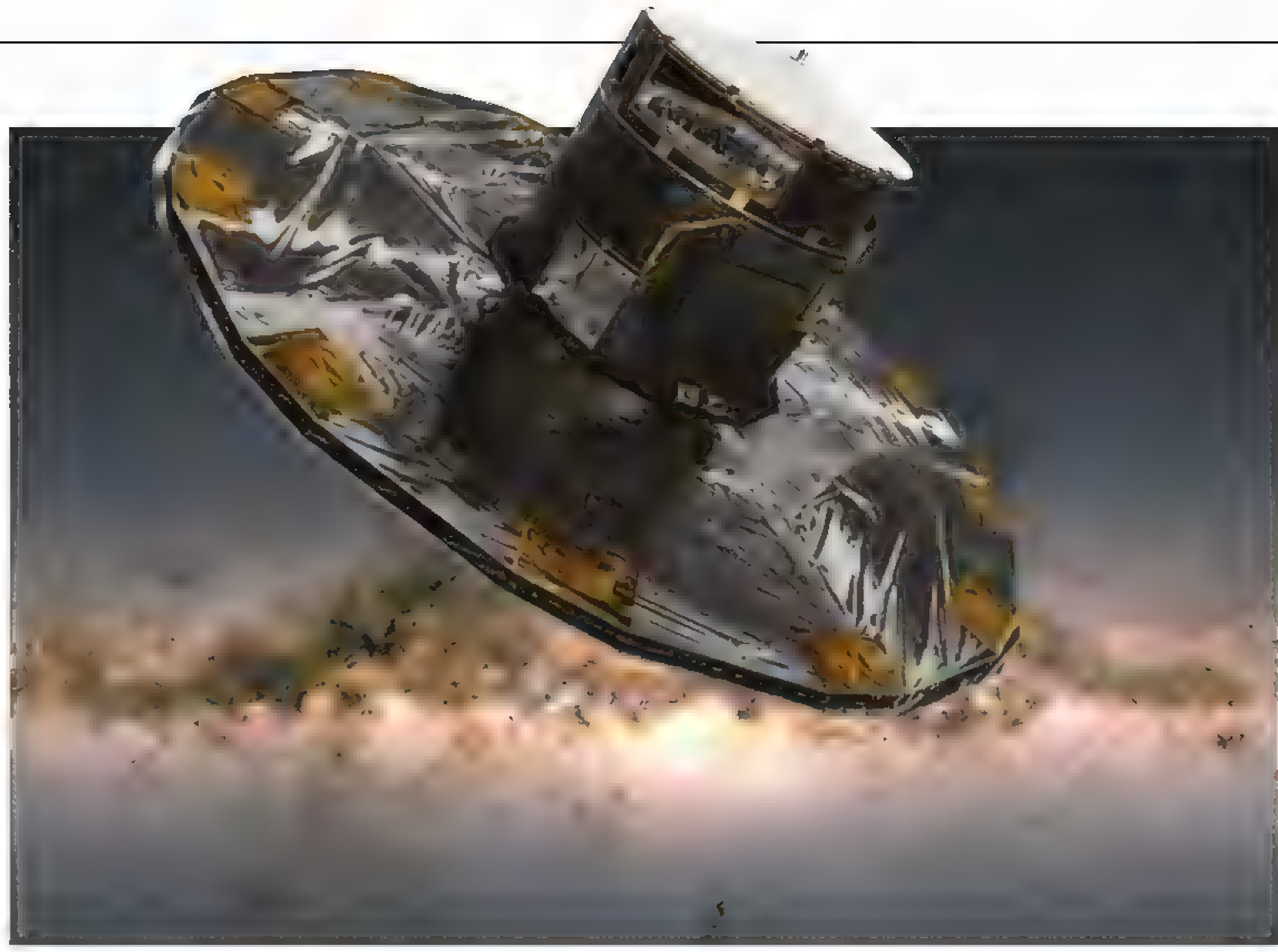
Larger giants
As a red giant brightens and swells in size, its surface cools because there is a far larger surface area for energy to escape through.

Type of star: RR Lyrae star
Mass: 0.65 times the Sun's mass
Radius: 5.0 times the Sun's radius
Temperature: 6,000°C (10,832°F)

Slower and stronger
Seismic waves in bigger red giants are more powerful, but have lower frequencies as they move more slowly in the low-density stellar interior.

Strange giant
RR Lyrae stars are an unusual group of helium-burning, low-mass giants found mostly in ancient globular clusters.

Cosmic lighthouse
These stars change in brightness every few hours, but Kepler data helps explain the long-term variations in their peaks and troughs.



other types of stars. A consequence was the advent of asteroseismology, whereby you're able to probe the interiors of stars other than the Sun through the use of their intrinsic oscillations."

Just like the characteristics of a guitar determine the frequency it oscillates at, the characteristics of a star determine the music its starquakes play. Things like the density and temperature of a material can change the speed at which sound moves through it. Larger stars tend to be hotter, and smaller stars cooler, whch means that trapped sound waves travel differently through stars of different sizes, mass and through the interiors of stars at varying evolutionary stages. Asteroseismology aims to reveal the internal structures of different stars, what they are made of and even how old they are by means of their intrinsic global oscillations. "There are several types or classes of stars that experience starquakes," Campante says. "Very often, the names of these classes are assigned after the name of a prototypical star, that is, the first star that was observed displaying that particular type of pulsating behaviour."

An example of this is Cepheid variables, which are stars that display periodic brightening and dimming. This 'blinking' is the result of large starquake oscillations causing the surface of Cepheids to pulsate, with the star expanding and then contracting while preserving its spherical symmetry. In addition to helping us learn about the interiors of these stars, the discovery of the relation between brightness and pulsation for Cepheids in the early 20th century provided astronomers with a way of measuring extragalactic distances. "Personally, I am particularly interested in oscillating Sun-like stars that are slightly smaller than the Sun," Campante explains. "Stars smaller and cooler than the Sun are characterised

The Gaia spacecraft mapped the stars of the Milky Way

The Sun experiences many violent phenomena besides starquakes, such as solar flares

DEAD STARS ARE STILL SHAKING

White dwarfs represent the final stage in the lives of stars with Sun-like masses, but stars with around eight times the mass of our star and greater end their lives as neutron stars. Neutron stars are perhaps the most extreme stellar bodies in the universe. They can spin as rapidly as 700 times per second, often blasting out jets of radiation that sweep over Earth like cosmic lighthouses. They possess the strongest magnetic fields in the known universe and they are comprised of matter so dense that if a tablespoon of it were brought to Earth, it would weigh about a billion tonnes.

Given that, it's probably unsurprising that neutron stars experience their own extreme class of starquakes. For neutron stars, starquakes happen when their crust experiences a sudden adjustment, which is more like an earthquake than starquakes for other stellar bodies. This can be caused by twisting magnetic fields in the interior of these dense stellar remnants or when the neutron star is forced to slow down by its dragging of space around it. Neutron star starquakes are responsible for launching powerful gamma-ray bursts, and recent research has suggested they may also generate mysterious and rapid blasts of radiation that sweep over Earth, called fast radio bursts.

by proportionally smaller convective fluxes, and thus find it increasingly more difficult to excite oscillations to the point that these can be detected by telescopes on Earth."

Campante is part of a team that made the relatively recent groundbreaking detection of the tiniest starquake that has ever been seen. They detected solar-like oscillations in an orange dwarf star called Epsilon Indi, which is located around 12 light years from Earth. The results were based on time-intensive observations collected using the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO), which is mounted on the Very Large Telescope (VLT) at the European Southern Observatory (ESO) in Chile. This detection conclusively showed that precise asteroseismology is possible for cool dwarfs down to temperatures of around 4,200 degrees Celsius (7,592 degrees Fahrenheit), which Campante says effectively opens up a whole new domain in observational astrophysics.

Some astroseismologists have their sights set on bigger targets that don't resemble the Sun today, but rather what it will look like in billions of years. In around 5 billion years the Sun will have exhausted its fuel for nuclear fusion in its core, and the energy that prevents its core from collapsing under its own gravity will cease. As the core of our star undergoes a collapse, the outer layers, where nuclear fusion is still happening, will swell out. This is called the red giant phase of stellar evolution, and it sees stars puff out to as much as hundreds of times their original width. For the Solar System, when the Sun enters its red giant phase, its outer layers will swell out to around the orbit of Mars, swallowing the inner planets, including Earth. Yet despite undergoing a dramatic change, observations of other red giants have shown starquakes continue during this puffed-out phase.

Listening to the music red giants make as they undergo starquakes is the business of Deheuvels. He explains that when studying starquakes in red giants,

> "The first detections of oscillations in the Sun date back to the 1960s and paved the way for the development of helioseismology"
>
> **Tiago Campante**

another type of mode is useful alongside p-modes. These are called gravity modes, and though they are gravity waves, they shouldn't be confused with gravitational waves, which are tiny ripples in the fabric of space-time as predicted by Einstein in his 1915 theory of general relativity. These particular gravity waves are created by the buoyancy of the plasma within stars – almost like waves created in the sea. "Some stars are known to oscillate with pressure modes. Other stars are known to oscillate essentially with gravity modes," Deheuvels says. "Red giants have oscillations we call 'mixed modes'. They behave like p-modes in the outer parts of a star – so in the red giant's puffed-out envelope – and gravity modes in the core. They have this dual nature, which is extremely interesting for us."

Gravity modes also exist in the Sun and other stars that are still in their hydrogen-burning main sequence, but they remain locked up in their stellar cores, with no coupling between these and gravity modes. "We don't really know what's happening in the very core of the Sun because we don't have access to these gravity modes," Deheuvels explains. "For red giants, since the modes are mixed, gravity modes have a large enough amplitude near the surface to be measured. What we have is almost like a magnifying glass on the core of the star. Since we have these mixed modes in red giants, they have become sort of a laboratory where we can test stellar physics."

Thanks to instruments like the Kepler Space Telescope and NASA's Transiting Exoplanet Survey Satellite (TESS), scientists have been able to measure starquakes for around 20,000 red giants. This has helped them determine the different speeds at which the exteriors and interiors of these stars rotate. When the cores of stars collapse, they retain their angular momentum, and thus are expected to speed up. This is just like an ice skater drawing in their arms to increase the speed of their spin. What the measurement of red giant starquakes has revealed is that

An illustration of the neutron star SGR 1806-20, which experienced the largest starquake ever seen

An illustration of a pulsating Cepheid variable star in a binary system

THE SMALLEST AND BIGGEST STARQUAKES EVER RECORDED

The smallest starquake recorded to date was detected in March 2024 and originated from Epsilon Indi, an orange dwarf star about 71 per cent the width of the Sun. "This makes Epsilon Indi at once the smallest and coolest dwarf star observed to date with confirmed solar-like oscillations; in other words, these are the tiniest starquakes ever detected," Campante says. "To give a flavour of the extreme precision level of these observations, the frequency of oscillations was 5,308 microhertz, and their peak amplitude was just 2.6 centimetres (one inch) per second, a mere 14 per cent of the oscillation amplitudes measured for the Sun. This is an outstanding technological achievement."

At the opposite end of the scale is a special form of starquake experienced by a neutron star. Detected in December 2004, the highly magnetic neutron star SGR 1806-20, located 42,000 light years away, experienced a starquake with a frequency of 94.5 hertz. This triggered a gamma-ray burst so powerful that in a tenth of a second it released as much energy as it would take the Sun 100,000 years to radiate. Had this starquake-launched gamma-ray burst occurred within ten light years of Earth, it would have been so powerful that it could have destroyed our planet's atmosphere, thus triggering an extinction-level event.

Sir Arthur Eddington, the father of astrophysics

the cores of these swelled-out stars are spinning slower than expected, setting up a mystery for astroseismologists to tackle in the future. Additionally, Deheuvels says red giant starquakes have been used to understand what magnetic fields look like inside stars.

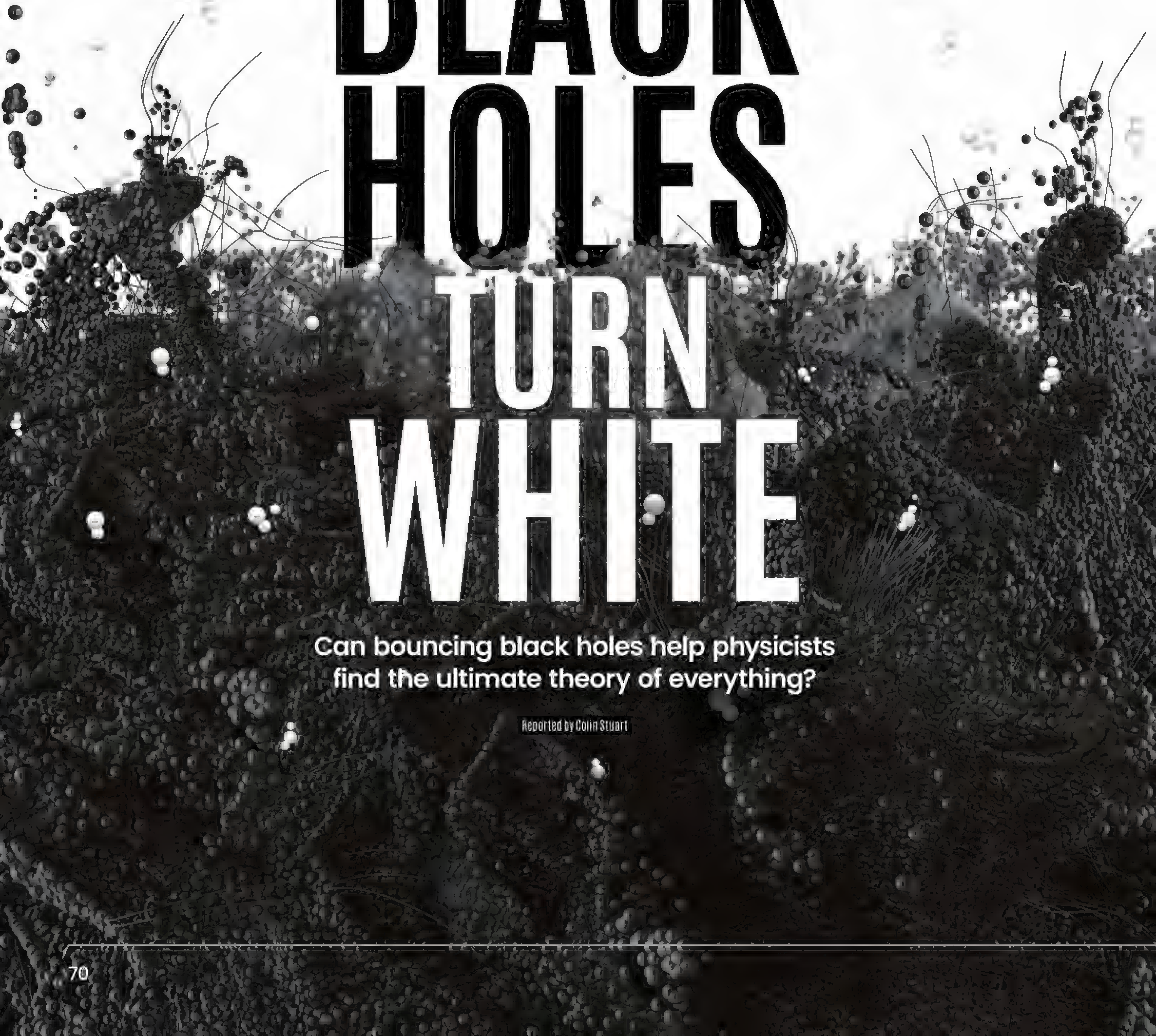
After spending around 1 billion years as a red giant, the outer layers of the Sun will cool and drift away, leaving a cloud of dimming stellar material called a planetary nebula. At the heart of this will be what was once the core of the Sun, now a smouldering ember called a white dwarf. However, what is interesting about white dwarfs, according to Deheuvels, is that some oscillate, experiencing starquakes, while others don't. "When the star is cooling as a white dwarf, it will cross something called an 'instability strip' in the Hertzsprung–Russell diagram of stellar evolution," he explains. "Some modes will become unstable during this period, and then we can see them oscillate. The good thing is a white dwarf is essentially the core of a star that has been stripped of its outer envelope. For a red giant, it's a bit harder to see the core because the envelope is there. But for a white dwarf, the entire envelope is gone and we can see directly into the core of the star."

Sir Arthur Eddington was a physicist and mathematician who could legitimately be considered the father of astrophysics, and by association, the study of the interiors of stars. In 1926, Eddington proclaimed: "At first sight it would seem that the deep interior of the Sun and stars is less accessible to scientific investigation than any other region of the universe." However, thanks to the study of starquakes, modern physicists now know Eddington was wrong.

"What I find fascinating is that just by looking at the periods of oscillation from the star, you can recover all sorts of information," Deheuvels says in conclusion. "You can see how it rotates, measure magnetic fields, see the sound waves, measure the speed of sound in stars and their chemical composition. The fact that we can do this for various types of stars with different masses and different evolutionary stages is really something very precious for physics in general."

Robert Lea
Space science writer
Rob is a science writer with a degree in physics and astronomy. He specialises in physics, astronomy, astrophysics and quantum physics.

WHEN BLACK HOLES TURN WHITE



Can bouncing black holes help physicists find the ultimate theory of everything?

Reported by Colin Stuart

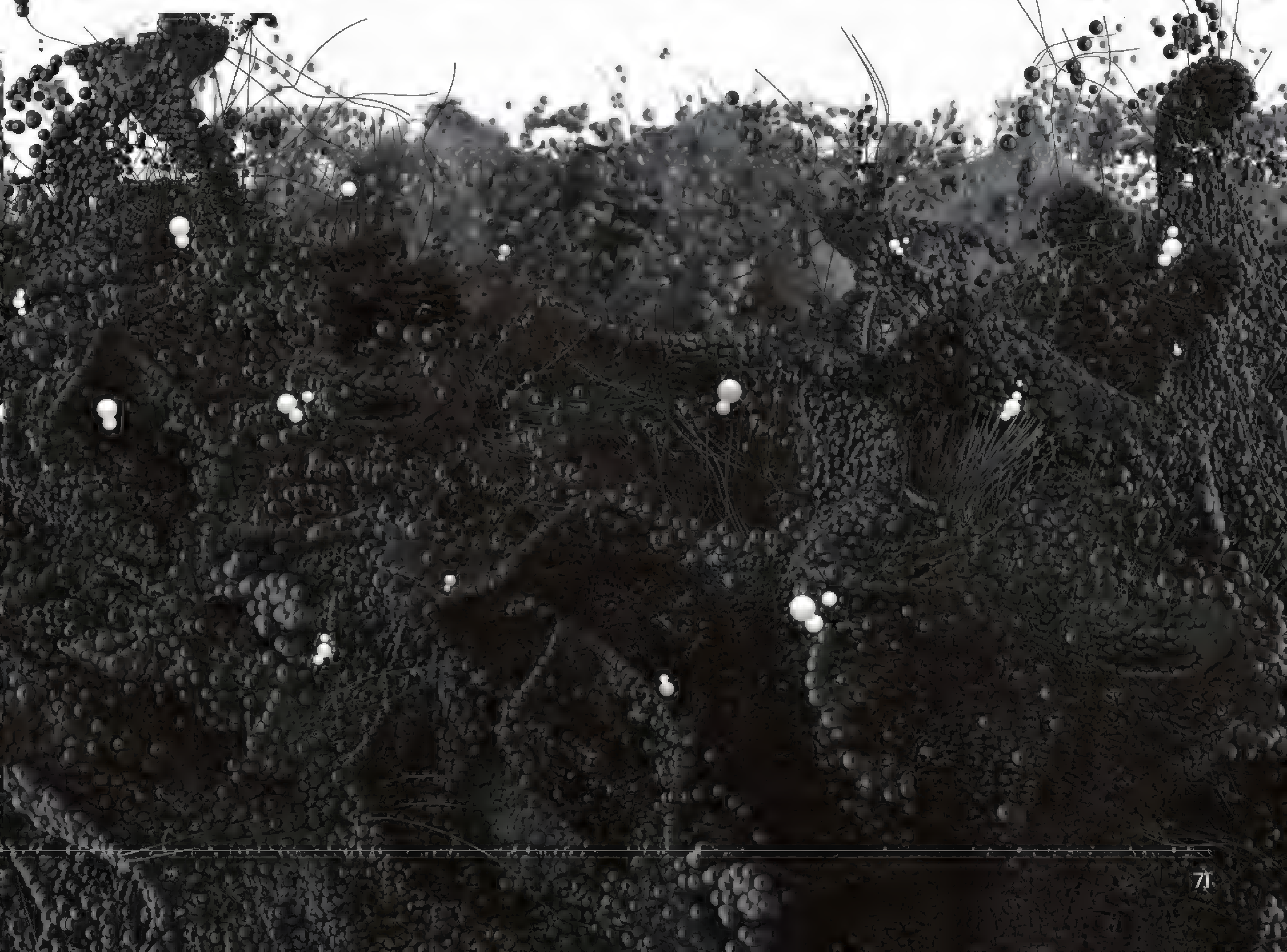
Somewhere out there in the vastness of space lurks a black hole smaller than the full stop at the end of this sentence. Minuscule but mighty, it could hold the key to unlocking some of the greatest mysteries in the universe. Black holes are the ultimate cosmic laboratory, a way for physicists to test out their theories in an environment so extreme that space and time are curved and warped. Even light cannot resist their eternal grasp, so we see no light reflected from them at all. We can only spot them when their gravity affects something visible or they merge to create gravitational waves. Few places have such a high amount of energy in such a small space.

But what happens if you fall into one? The bad news is you're unlikely to survive the ordeal. The difference in gravity between your feet and your head would eventually get so extreme that it would overcome the forces holding your atoms together. You'd be torn apart into thin strips of human spaghetti, which is where the process gets its whimsical name: spaghettification. But where do your spaghettified atoms ultimately end up? What's at the bottom of a black hole?

WHAT IS A WHITE HOLE?

Black holes are places where you can go in but you can never escape, while a white hole is a place you can leave but can never go back in

Our best answer currently comes from our leading theory of gravity: Einstein's general theory of relativity. It tells us that a singularity awaits – an infinitely small, infinitely dense point where space and time cease to be. Hit it and you're immediately erased from existence. Yet if you crush something down much smaller than an atom, you enter the arena of quantum physics. At the moment we're yet to take its weird and wonderful rules into account at the bottom of black holes because we have no proven way of combining it with general relativity, although recent research from Aalto University is very promising. The search for such a theory of 'quantum gravity' is the ultimate goal for many physicists. It might also help us explain where our cosmos came from because, according to general relativity, the other place you find a singularity is at the moment of creation – the Big Bang, where time and space sprang into existence.



Carlo Rovelli, director of the quantum gravity group at Aix-Marseille University in France, doesn't believe in singularities. "You cannot compress things too much," he says. "It is a universal thing in nature." He argues we need quantum gravity to help explain what happens instead. Rovelli is a founder of one approach to this thorny problem of getting the two theories to play nicely together: loop quantum gravity (LQG). According to Einstein, the fabric of space-time is smooth. However, proponents of LQG suggest that it isn't. "That's not surprising," says Rovelli. "Other things in the universe like light and the energy of electrons come in chunks." He suggests space is not smooth, but grainy – it's also made of tiny little chunks, or loops. Think of it like a piece of cloth; at first glance it may seem smooth, but look at it under a microscope and you'll see that it's really made of a series of stitches. If you apply this logic to the depths of a black hole you get a remarkable result. Occasionally a black hole might 'bounce' into its polar opposite: a white hole. "With a black hole you get sucked in, but with a white hole things can only come out," says Francesca Vidotto from Western University.

What exactly triggers the change? According to Vidotto, it's simple chance. Quantum physics is defined by probability. You can never say exactly where an object is or what state it is in, only where it is more likely to be when you make a measurement. But the smaller an object, the more likely it is for unusual things to happen. Vidotto says an object has a timescale over which it can display these weird quantum properties. "For large objects, like a person, this time is much larger than the age of the universe," she says. "For a planet-sized black hole it's about the age of the universe." But for a black hole just half a millimetre across, you'd expect it to have happened fairly often already across the cosmos. We normally think of black holes as much bigger than that – formed by the deaths of the most massive stars. However, astronomers also imagine there may be primordial black holes out there. Tiny ones formed in the early universe shortly after the Big Bang. Some of those could now be making this odd transition into a white hole.

ETERNAL BLACK HOLE THEORY

White holes belong in the theory of eternal black holes: concepts that widely assume that matter that enters a black hole is permanently lost and past the point of no return

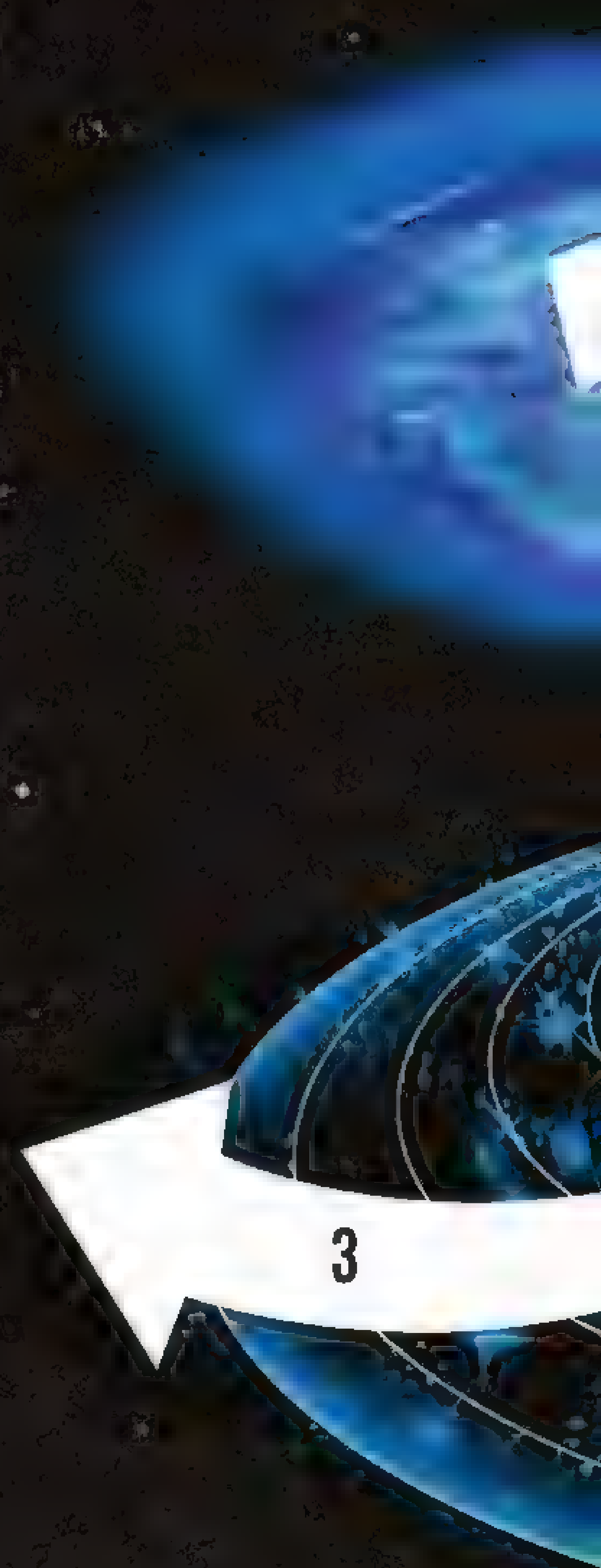
"With a black hole you get sucked in, but with a white hole things can only come out"

Francesca Vidotto

Successors to gamma-ray telescopes like NASA's now-defunct Swift might detect radiation from black holes bouncing into white holes

MEET THE WHITE HOLE

What do we know about these mysterious objects?



1 Black hole forms Black holes form when a massive star dies, but primordial black holes are also thought to have appeared shortly after the Big Bang.

2 Sculpting a singularity According to Einstein, an infinitely small, infinitely heavy point called a singularity forms at the bottom.

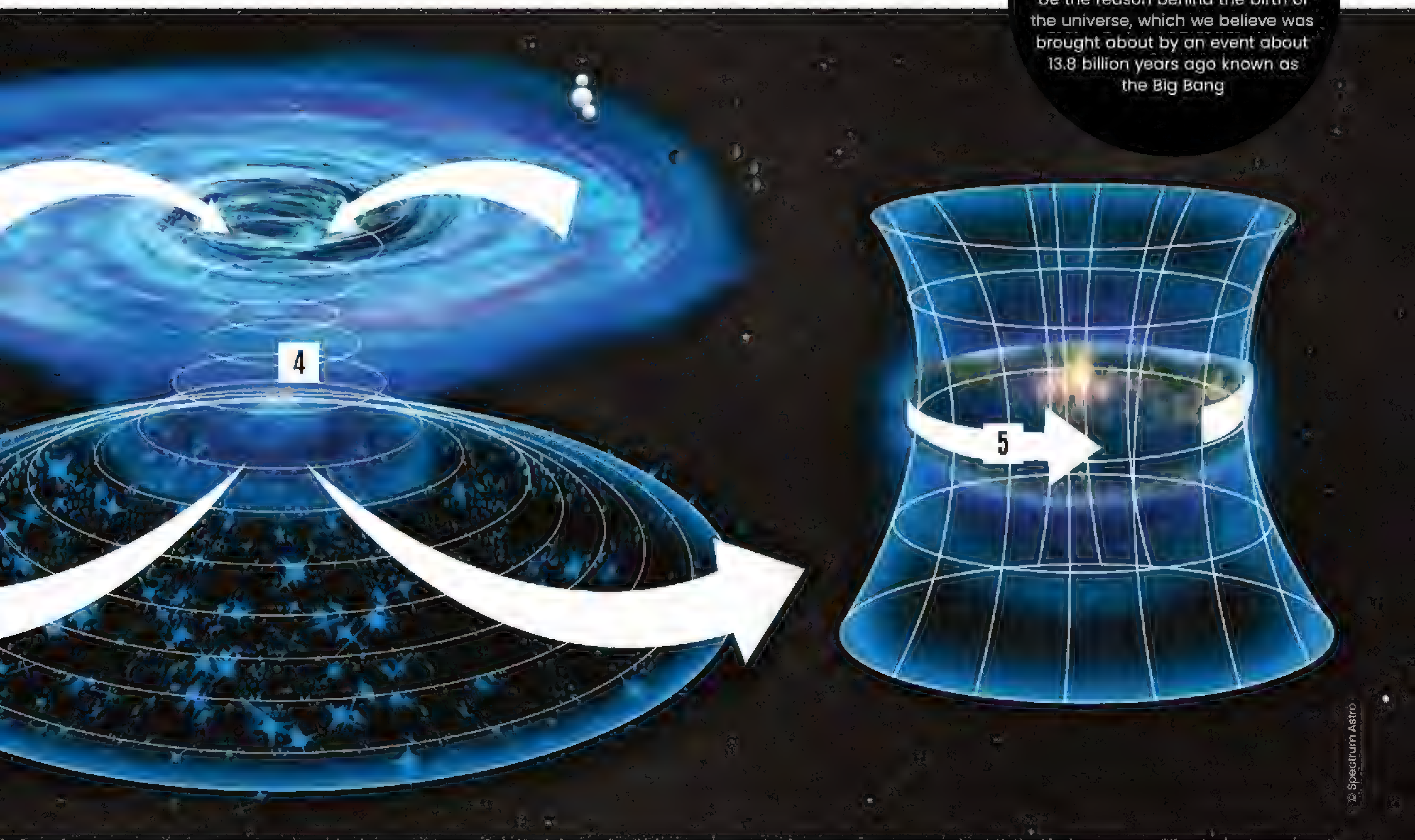
3 Pushed into the past You're eventually spat out of a white hole, and it's an object you can never return through.

4 Wormhole A bridge opens up between the present and the past, known as an Einstein-Rosen bridge or a wormhole.

5 Spinning singularities A rotating black hole would form a ring-shaped singularity with a hole in the middle rather than a single point.

WHITE HOLES AND THE BIG BANG

An intriguing idea suggested by cosmologists implies that a 'matter-spewing' white hole could be the reason behind the birth of the universe, which we believe was brought about by an event about 13.8 billion years ago known as the Big Bang



© Spectrum Astro

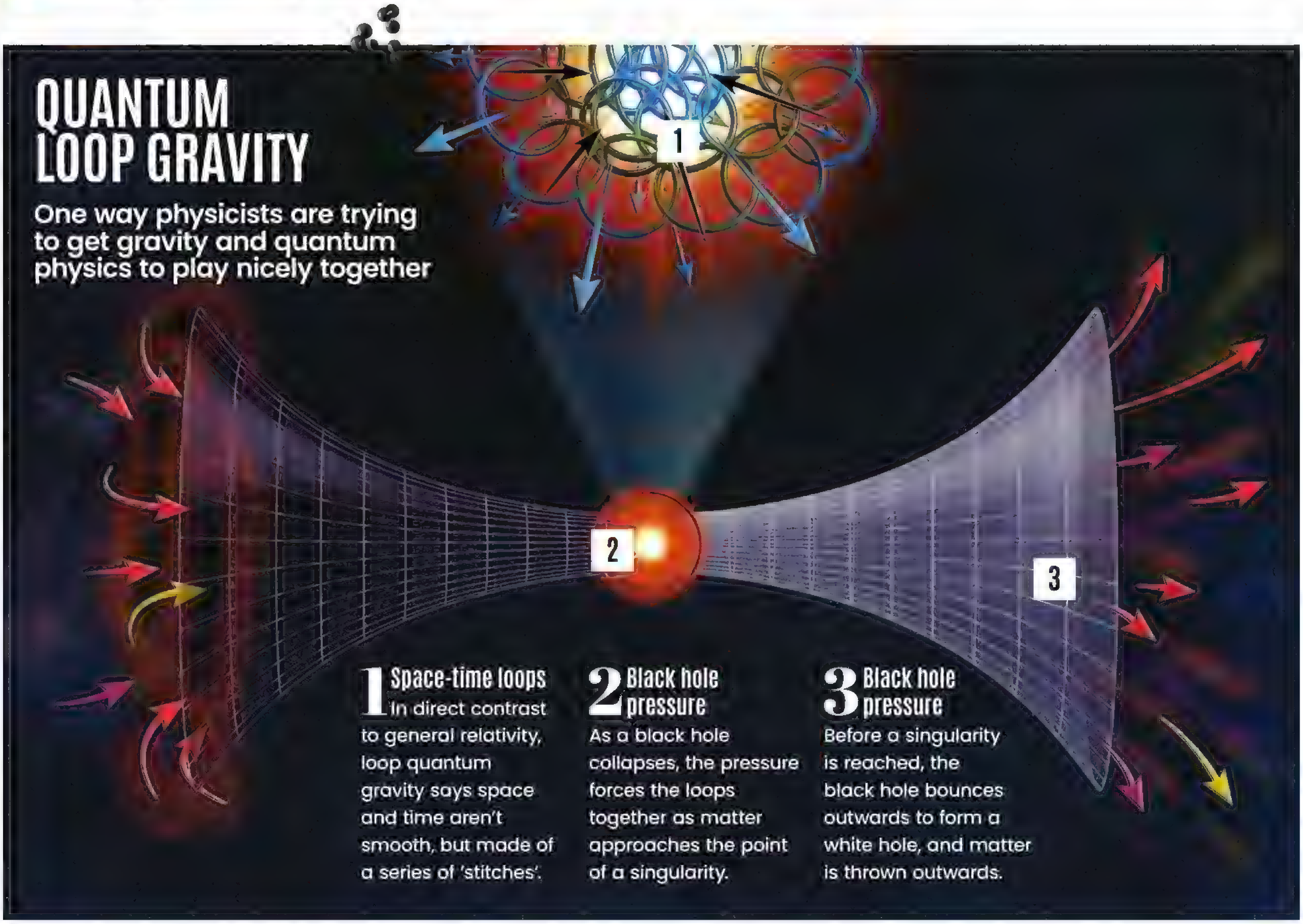
If that's true, we should be able to see evidence of it happening with our telescopes. "You would expect an explosion," says Vidotto. Such a detonation would trigger the rapid release of huge amounts of energy. How energetic this radiation is depends on the size of the black hole. For black holes the size of your hand or smaller, you'd expect it to be the radio part of the spectrum. And astronomers have found a handful of unexplained events that might just fit the bill: fast radio bursts (FRBs).

The first was spotted in 2007, and while there are still many mysteries surrounding them, it's clear they are coming from beyond our galaxy. The nearest emanated from over a billion light years away. Some astronomers have even suggested they might be attempts by aliens to get in contact. Far more likely is that they have some astronomical origin, but what? Perhaps they are generated by colliding black holes or neutron stars. However, there is a way we might be able to prove that they really are coming from black holes bouncing into white holes.

According to calculations by Rovelli and Vidotto, more distant bursts should have more energy than those nearby because black holes are thought to evaporate over time by releasing radiation. Younger black holes in the distant universe should therefore be bigger and release more energy than older black holes closer to us that have had more time to evaporate.

This is in direct contrast to the way things normally work in astronomy. As the universe expands it dilutes the amount of energy in a given amount of space. There's more space between us and a distant object to stretch, so faraway objects have their energy watered down more than those close to us. With bouncing black holes you'd expect the two effects to cancel each other out, meaning these explosive events would have a similar energy across a wide range of cosmic distances.

There are some potential snags, however. The FRBs discovered so far are not of the exact energy you would expect from a black hole to white hole bounce. But that may not be the end of the world, according to Hal Haggard from Bard College in New York. "Given how imprecise the calculations are it's not surprising," he says. "It's in the right ball park." More concerning is that



QUANTUM LOOP GRAVITY

One way physicists are trying to get gravity and quantum physics to play nicely together

1 Space-time loops In direct contrast to general relativity, loop quantum gravity says space and time aren't smooth, but made of a series of 'stitches'.

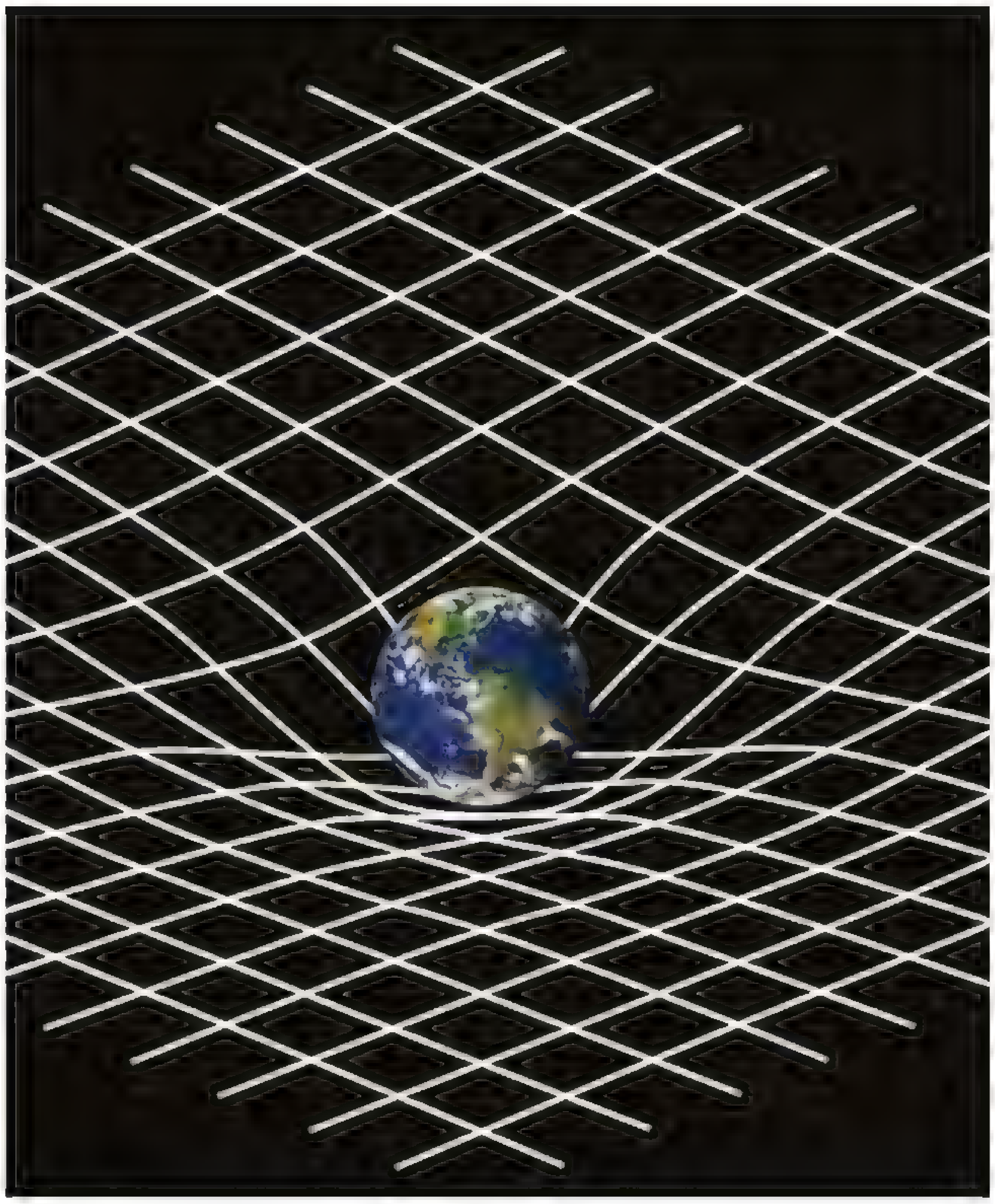
2 Black hole pressure As a black hole collapses, the pressure forces the loops together as matter approaches the point of a singularity.

3 Black hole pressure Before a singularity is reached, the black hole bounces outwards to form a white hole, and matter is thrown outwards.

astronomers have identified a repeating FRB called FRB 121102. First discovered in 2012, more than 15 distinct pulses are associated with the same source. "There's nothing in the white hole theory that calls for that," says Haggard. "If more of these repeating bursts are found, that goes against this proposal."

He believes the white hole interpretation is extremely speculative, but the payoff is potentially huge. "It's exciting because there are so few ways to test quantum gravity currently on the table." But confirming a black to white hole transition wouldn't immediately crown LQG the victor. Haggard says the approach taken so far is "a generic model that doesn't leverage anything specific about the theory of quantum gravity you're using". However, detailed observations of how the explosions played out could do the trick. "Detailed analysis of the signals would be able to distinguish between theories, and that's why this is so exciting," says Haggard.

Given the high stakes, there are other ways a black hole to white hole bounce could show itself. According to Vidotto, the explosive event should also generate



"It's exciting because there are so few ways to test quantum gravity"

Hal Haggard

SECRET INGREDIENT TO DARK MATTER

According to recent research, these black hole opposites could constitute dark matter, the mysterious substance that forms a decent proportion of matter in the universe

❶ Differences in the strength of gravity across an object stretch it as it approaches a black hole

❷ Einstein said that space and time are woven together into a smooth continuous fabric called space-time

❸ Although invisible, a black hole can often be detected by its effect on its surroundings

gamma rays. Although we do already have gamma-ray telescopes peering into the universe, Vidotto says "they are not yet optimised to see in such high-energy gamma rays". Future observatories may well be up to the task. In the meantime, there's a third way in: synchrotron emission. Particles like electrons would be accelerated through strong magnetic fields during the high-energy explosion, emitting radiation as they do so. "The challenge is how we can distinguish these cosmic rays from all the other sources in the sky," says Vidotto.

If any one of these endeavours is successful, confirming a black hole to white hole transition won't just help with the mystery of quantum gravity. It could also tackle an equally perplexing puzzle: dark matter. When we look at galaxies and clusters of galaxies there appears to be far more gravity than can be accounted for using visible material like stars and gas alone. Instead astronomers have suggested there is some hidden material skulking in the shadows which acts like a galactic glue, helping bind galaxies together with its own gravitational pull. The most fashionable contender for dark matter has been supersymmetry – the idea that alongside the familiar subatomic particles like electrons and protons there are bigger particles that are their mirror images. The lightest of these supersymmetric particles has been the go-to explanation for dark matter for well over a decade. But despite a lot of searching, no one has ever found a supersymmetric particle.

That's causing physicists to look elsewhere for an explanation. Rovelli believes the remnants left behind as a black hole transitions into a white hole could go some way to providing the missing gravity. Being so small, they would be hard to detect other than by their collective gravitational pull. "What's remarkable is that no new physics is needed. No strings, no new forces and no new particles," Rovelli says, referring to string theory – an alternative way to attack the problem of quantum gravity. Haggard agrees it's possible "they could make up a substantial fraction of dark matter". He also says that "dark matter may not be one thing – it may be a mixture of particles we haven't discovered and something else". That something else could be black holes turning white.

For now, astronomers are left in a tantalising position. Through FRBs we might not only have the first clues that black holes can morph into their polar opposites, but also a way to tackle the ultimate questions about the nature of space and time itself. Then again, we may not. Only more observations with more telescopes from one end of the electromagnetic spectrum to the other will tell us whether to call the Nobel committee or return to the drawing board. The stakes couldn't be higher.

Colin Stuart
Astronomer and space science writer
Colin holds a degree in astrophysics, has written over 17 books on space and even has an asteroid named in his honour: 15347 Colinstuart.

▲ Until we can detect and measure a white hole, we don't know how they'd look

▼ Could dark matter be made up of black holes?

OUR HUNT FOR THE WHITE HOLE

How might an 'inverse black hole' show itself to our telescopes?

1 Radio waves

As a small black hole bounces into a white hole, it should produce radio waves approximately the size of your hand.

2 Journey across the universe

Travelling at the speed of light, they still take billions of years to cross the universe and enter the Milky Way.

3 Parabolic reflector

They hit the large part of the radio dish, which is shaped to bring radio waves to a common focus.

4 Subreflector

A smaller reflector is placed at the common focus point to collect and send the corralled radio waves downwards.

5 The feed horn

The radio waves pass through the feed horn, which as its name suggests feeds the signal deeper down into the radio telescope.

6 Analysis by astronomers

Only after these stages can astronomers analyse the details of the signal in order to see whether it matches what's expected.

7 The receiver and amplifier

Finally, the radio signals are received, before being amplified in order to make them easier to analyse by computers.

ROGUE PLANETS

ORPHAN PLANETS RIPPED AWAY FROM THEIR STELLAR PARENTS OR BORN IN ISOLATION MAY VASTLY OUTNUMBER STARS

Reported by Robert Lea

Ever since astronomers first began discovering planets outside of the Solar System, dubbed 'exoplanets' in the mid-1990s, our picture of the Solar System as a 'typical' arrangement of planets and stars has been turned on its head. Among the 6,000 or so exoplanets that we have discovered over the course of the last three decades are scorching hot worlds bombarded by so much stellar radiation that they rain molten metal; planets that race around their stars so fast they can fit several years into a single day; and planets squashed by the gravity of their stars so much they have flattened discs. While all of these discoveries have changed our perspective of the Solar System and its planets being 'typical' – and may actually have even made our corner of the Milky Way look slightly mundane by comparison – they all share a similar theme: planets orbiting stars, albeit sometimes strangely, violently or chaotically.

The first rogue planet was found around 2000 but then in 2012, astronomers operating the Canada-France Brown Dwarfs Survey discovered the most convincing and closest example of a rogue planet – a cosmic orphan that drifts through the cosmos away from a parent star. Rogue planets go by a range of alternative names, including interstellar, nomad, orphan, starless, unbound or wandering planets, but the more official names for these worlds are free-floating planets (FFPs) or isolated planetary-mass objects (iPMOs).

So-called 'failed stars' called brown dwarfs can add confusion to proceedings. These are objects with masses up to around 12 times that of Jupiter – just outside the range of the largest planets – which form in isolation like stars but never quite gather enough mass to trigger the nuclear fusion of hydrogen to helium in their cores. Because they also wander the universe alone, it can be difficult to distinguish brown dwarfs from high-mass rogue planets.

The planetary rogues discovered thus far are merely the tip of the iceberg. In 2023, a nine-year survey called Microlensing Observations in Astrophysics (MOA), conducted by scientists from NASA and Japan's Osaka University, suggested that rogue planets in the Milky Way far

> "Because they also wander the universe alone, it can be difficult to distinguish brown dwarfs from high-mass rogue planets"

HOW TO FIND A *ROGUE PLANET*

Gravitational microlensing

Microlensing is the distortion and magnification of a star's light that happens when another object passes in front of it and bends the path of light passing near it through gravity. It's been successfully used to find exoplanets orbiting other stars, but can also be used to detect interstellar planets, allowing astronomers to estimate how common they are. Unfortunately, microlensing events by interstellar planets tend to be one-offs, so it's hard to learn much about the planets themselves.

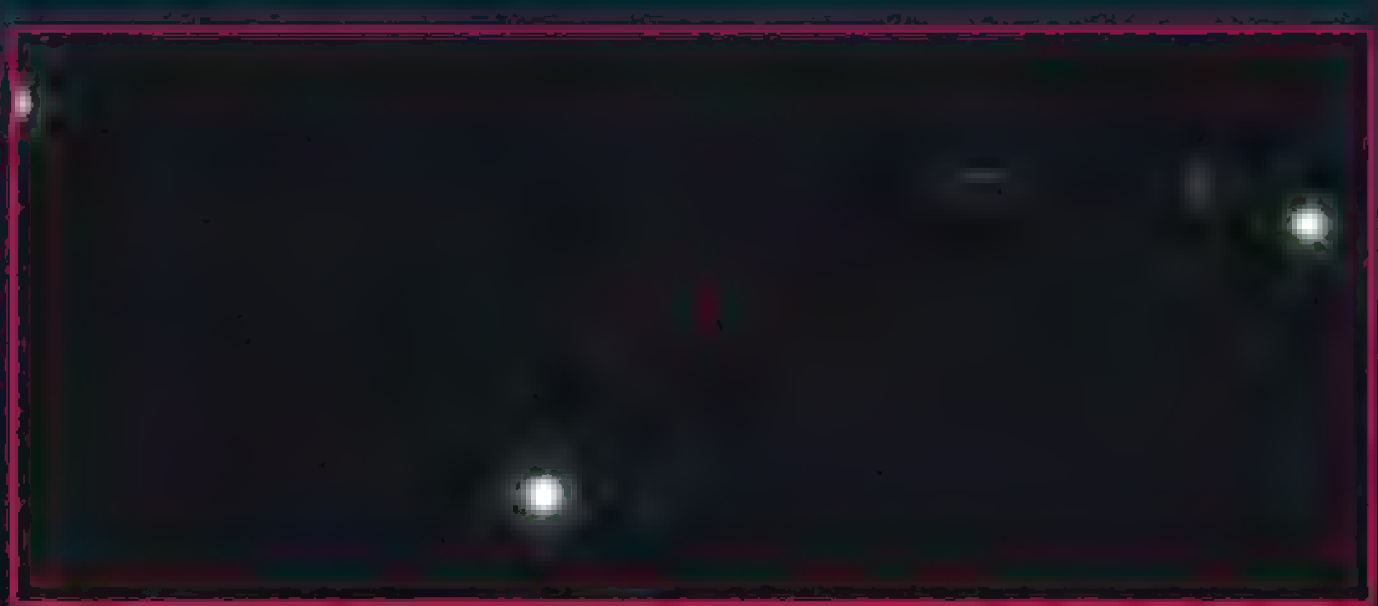
Microlensing at work
This diagram shows how microlensing reveals exoplanets in orbit around stars, but the principle is the same for rogue interstellar planets.

1 Orbiting planet A star closer to Earth is orbited by an unseen planet.

2 Distant starlight Light emitted from a distant star spreads out on straight-line paths in all directions.

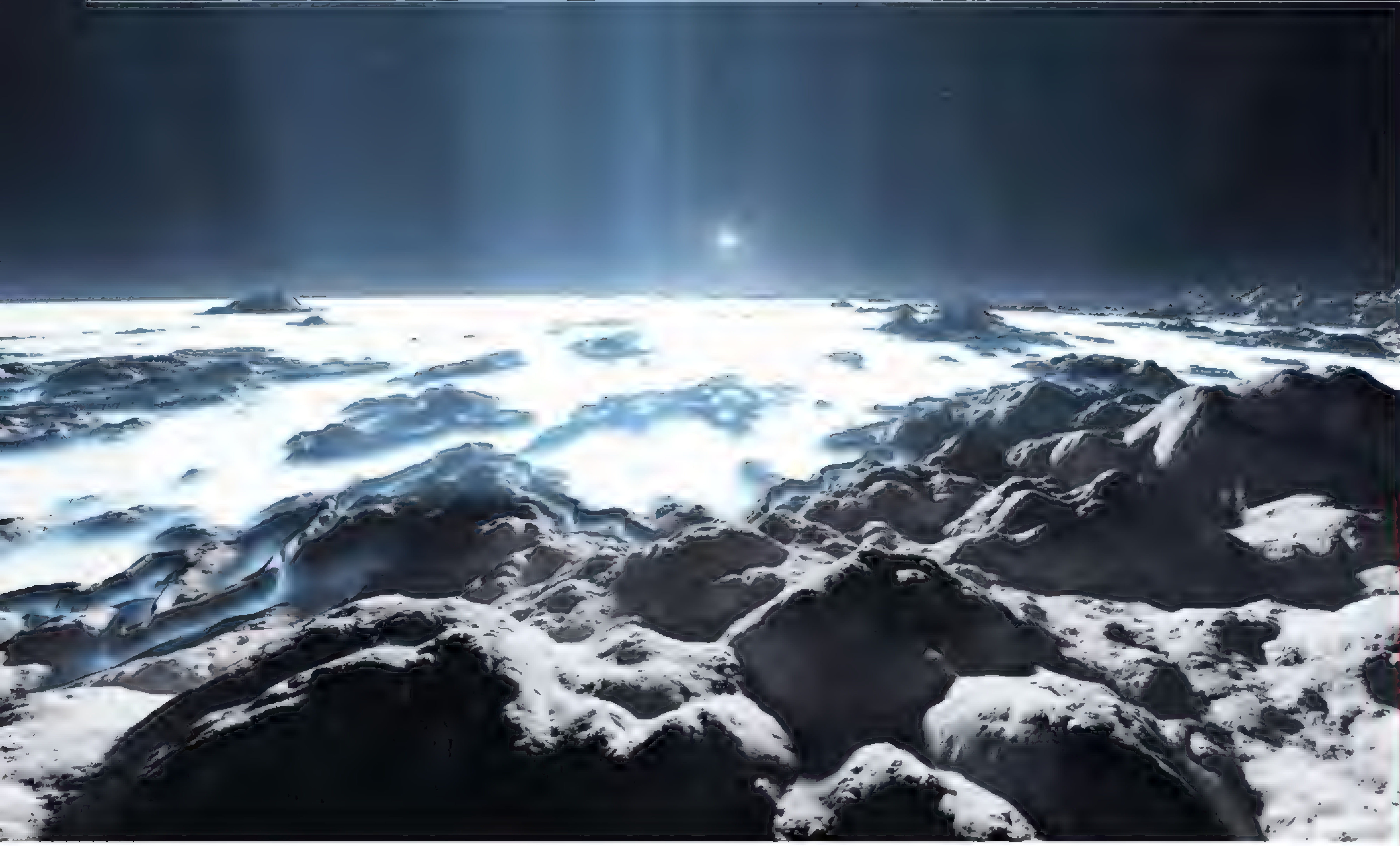
3 Distorted light As the distant star's light passes close to the planet, some of it is bent towards Earth.

4 Magnified image Astronomers see the starlight from the object distort and brighten in a certain way.



Direct imaging

The direct detection of interstellar planets relies on long-exposure surveys of large areas of the sky looking for brown dwarfs and other faint objects. Infrared surveys are particularly useful since many of these objects emit more radiation as heat than they do as light. Surveys often target areas of recent star formation, where objects are likely to be at their youngest and therefore hottest and brightest.



outnumber planets that orbit stars, also outnumbering those stars by around 20 times. "Rogue planets could vastly outnumber the stars in the Milky Way. There are 1 to 300 billion stars in the Milky Way, so there could be trillions of free-floating planets," NASA's Jet Propulsion Laboratory postdoctoral fellow Samson A Johnson told **All About Space** magazine. "The fact that we're finding any at all means there's a lot, but just exactly how many is a lot is hard to say right now."

Just how do these planets come to be cosmic orphans? There are two possible ways that planets can end up wandering the Milky Way isolated from a parent star. Which mechanism led to the rogue planet's existence as a cosmic orphan depends strongly on its mass. Johnson explains that large rogue planets with masses around that of Jupiter and greater are likely to form in a similar way to stars. Giant clouds of gas and dust called interstellar molecular clouds exist within galaxies and between stars. When patches of these clouds cool and become overdense, they collapse to form protostars. If these stars can gather enough mass from what remains of the cloud, they become full-fledged stars; if not they become brown dwarfs. But the collapse of these dense patches of molecular clouds can also create isolated Jupiter-mass rogue planets that never had a parent star.

For rogue planets that have masses closer to that of Earth, the story is different. "The other way that you can form free-floating planets is by ejecting them from planetary systems," Johnson says. "There are two ways this could happen. First, it could happen when the planetary system is forming." Planetary formation around an infant star is an incredibly chaotic process. There are lots of different dynamics going on, with objects ranging in size from dust grains to planets flying around. "There's a lot of things that can happen," Johnson continues. "The most likely thing is that some massive planet, the bully of the system, will start kicking things around just because it has a lot of mass to throw about. This planetary bully can put lower mass

A An artist's impression showing the surface of a frozen planet

YOUNG ROGUE - CFBDSIR 2149-043

Spotted in 2012 as part of the Canada-France Brown Dwarfs Survey, CFBDSIR 2149-043 was important because its young age provided evidence for planetry-mass objects forming in isolation. However, the possibility does remain that it is actually a low-mass brown dwarf. Located around 130 light years from Earth in the constellation of Aquarius, if CFBDSIR 2149-043 is a rogue planet, it is one of the closest to Earth ever seen. Not only that, but the object would also be one of the few planetary orphans discovered by direct imaging.

objects on larger orbits, or it can toss them out of the planetary system altogether."

These ejected objects are likely to have masses around that of Mars, with some even possessing higher masses equivalent to Earth's. As for the speed at which the planets are ejected, Ohio State University physicist Scott Gaudi explains that it depends on where around its star the planet was located. "If they were ejected from the outer part of the planetary system, then rogue planets will have a speed that's only slightly different than the velocity of the nearby stars – a few tens of kilometres per second," Gaudi says. "To get ejected from closer in, rogue planets have to be kicked out with a much higher velocity." As an example, for Earth to be ejected from the Solar System its velocity around the

CFBDSIR 2149-043 was the first rogue exoplanet to be discovered by direct imaging

WANDERING WORLDS WE'VE FOUND SO FAR

Cha 110913-773444

529 light years

Direct observation

Chamaeleon

Discovered in 2004, Cha 110913-773444 has the mass of about eight Jupiters, making it a candidate interstellar planet. Infrared observations show that it is surrounded by a faint disc of planet-forming material, perhaps moons in formation?

WISE 0855-0714

7.4 light years

Direct observation

Hydra

Discovered in 2014 using the Wide-field Infrared Survey Explorer, this small object is a little over seven light years away. It's either a cold, low-mass brown dwarf or an interstellar planet on our cosmic doorstep.

PSO J318.5-22

80 light years

Direct observation

Capricornus

PSO J318 is the best studied interstellar planet so far, with a tightly constrained mass and age that indicate it is undoubtedly a planet rather than a brown dwarf. It was discovered in 2013.

CFBDSIR 2149-0403

130 light years

Direct observation

Aquarius

CFBDSIR 2149-0403 seems to be part of the AB Doradus Moving Group, a group of recently formed stars that's 50 to 120 million years old. Its mass is likely to be between four and seven Jupiters, although there is debate over its classification.

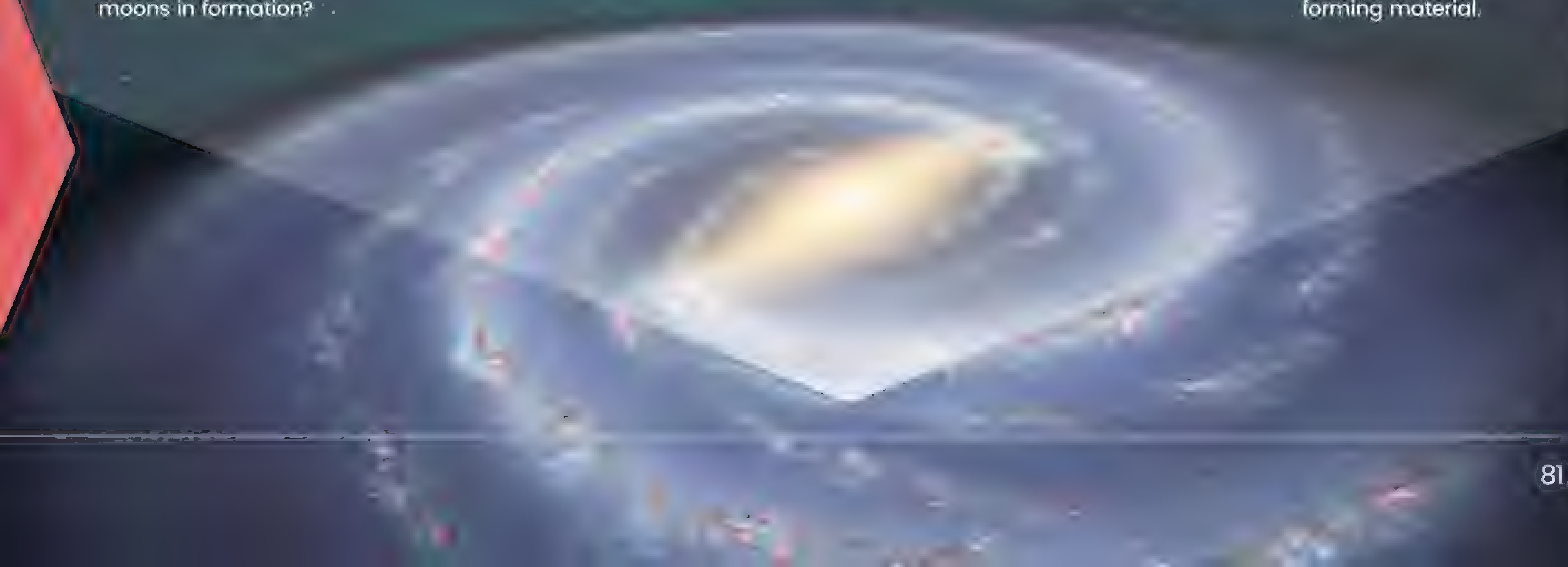
OTS 44

554 light years

Direct observation

Chamaeleon

This faint young object has a mass between 6 and 17 Jupiters, putting it on the boundary between brown dwarf and planet. Excessive infrared radiation from its surroundings suggests it's shrouded by a disc of planet-forming material.



WHAT IF A *ROGUE PLANET* ENTERED OUR SOLAR SYSTEM?

If a new Ju[illegible]
plane of the [illegible]

1 Uranus and Neptune
More loosely bound to the Sun's gravity, the Solar System's outer ice giants might be most vulnerable to having their orbits disrupted, perhaps drifting away into interstellar space or falling into orbit around the visitor.

2 Earth
If Earth's orbit became more elliptical, it would present a severe danger to all life, as the amount of sunlight reaching the surface would become more variable and summers and winters more extreme. The Moon might shield us from the worst effects of asteroid bombardment, though.

3 Mercury
As the closest planet to the Sun, Mercury's orbit is tightly bound by solar gravity, so it would probably survive more or less unchanged.

4 Venus
Venus might find its almost perfectly circular orbit disrupted into an ellipse. This could upset its slow rotation period and alter the Venusian climate.

5 Mars
If the orbit of Mars was nudged closer to the Sun, Mars could actually become more hospitable as its icecaps melted and its atmosphere thickened. But it would take the brunt of bombardment from asteroids.

6 Asteroid belt
The countless small bodies orbiting between Mars and Jupiter would undoubtedly be disrupted by a rogue world. Some might be thrown out of the Solar System entirely, but others, along with comets from beyond Neptune, would rain down on the inner Solar System, causing huge impacts.

7 Jupiter
As the Solar System's largest planet, Jupiter would be best able to withstand the disruption of a rogue planet passing by. Its gravity would draw in many of the comets falling in from the edge of the Solar System.

8 Saturn
Saturn, the second most massive planet, would probably also survive, but its famous ring system might not withstand the disruption of the rogue planet's gravity and the bombardment of cometary debris carried with it.

Sun of about 30 kilometres (18.6 miles) per second would have to be squared.

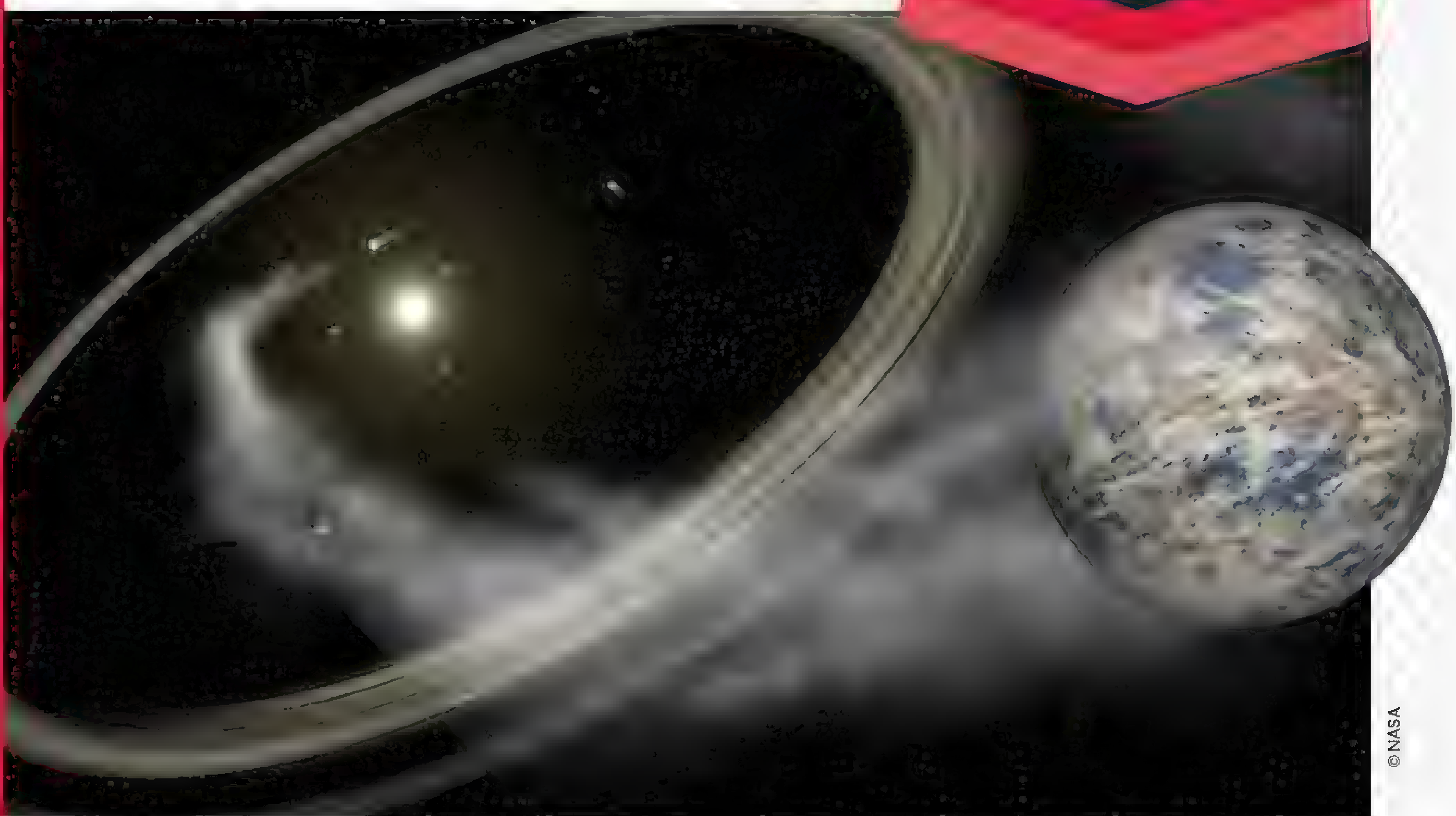
All this means that discovering rogue planets and then tracing them back to their former planetary systems has the potential to teach scientists a great deal about planetary formation. "I think rogue planets are interesting from a planet formation perspective because the low-mass ones are most likely to be orphaned by ejecting them from their planetary systems during formation," says Gaudi. "So rogue planets provide a way of measuring how chaotic and violent planet formation might be." Gaudi also adds that by accounting for the total mass of free-floating planets, scientists could learn something about how much mass is contained in the discs of gas and dust that surround infant planets in so-called 'protoplanetary discs', how much of it remains in mature planetary systems and how much is ejected.

Johnson explains that the other way a planet can be tossed from a planetary system happens at the opposite end of a star's life cycle, during its red giant phase. After billions of years of burning hydrogen at their cores, stars eventually run out of this fuel for nuclear fusion. As these stars undergo their death throes, their cores collapse under the influence of their own gravity, but the outer layers where nuclear fusion is still happening, puff out. This is known as the red giant phase of the star's life, and it can see the star swelling to between ten and 100 times its original width. It's followed by the further dispersal of this shed stellar material, leaving the stellar core as a white dwarf stellar remnant. This evolution and the upheaval it causes in the

A SOLAR SYSTEM ROGUE?

Could the Solar System once have harboured its own soon-to-be orphaned planet? Gaudi thinks the chances are high, but suspects that evidence may be difficult to obtain. "There are lots of reasons to expect that at least one pretty massive planet was ejected," Gaudi says. "We see that the giant planets Jupiter, Saturn and Neptune have migrated a significant amount during the Solar System's 4.5-billion-year history. Part of that migration would have involved ejecting low-mass bodies near those giant planets."

Gaudi adds that if there was a planet that had been completely ejected from our Solar System, this would have happened around 4.5 billion years ago. That means that any potential Solar System rogue planet will now have moved so far away from Earth and from the Solar System that Gaudi thinks it would probably not be detectable by any means that we can conceive of right now.



© NASA

COULD JUMBOS CONFUSE THE ROGUE PLANET PICTURE?

A discovery made in late-2023 with the James Webb Space Telescope could really throw theories surrounding rogue planets into question. Astronomers discovered 42 pairs of free-floating planets with masses around that of Jupiter in the Orion Nebula. These pairs of Jupiter-mass binary objects, or JuMBOs, challenge planet-ejection theories. That's because the process of exiling a planet should split it up from any binary companion it has, yet JuMBOs exist in pairs. The fact that then-European Space Agency senior science advisor, Mark McCaughrean, and company discovered 42 pairs of these weird objects also suggests their ejection as a unit wasn't merely some freak event.

Likewise, with masses more than a few times that of Jupiter, it seems improbable that JuMBOs formed like stars. That is because the probability of finding a star in a binary falls off rapidly as mass decreases, approaching zero for brown dwarfs, which are more massive than JuMBOs.

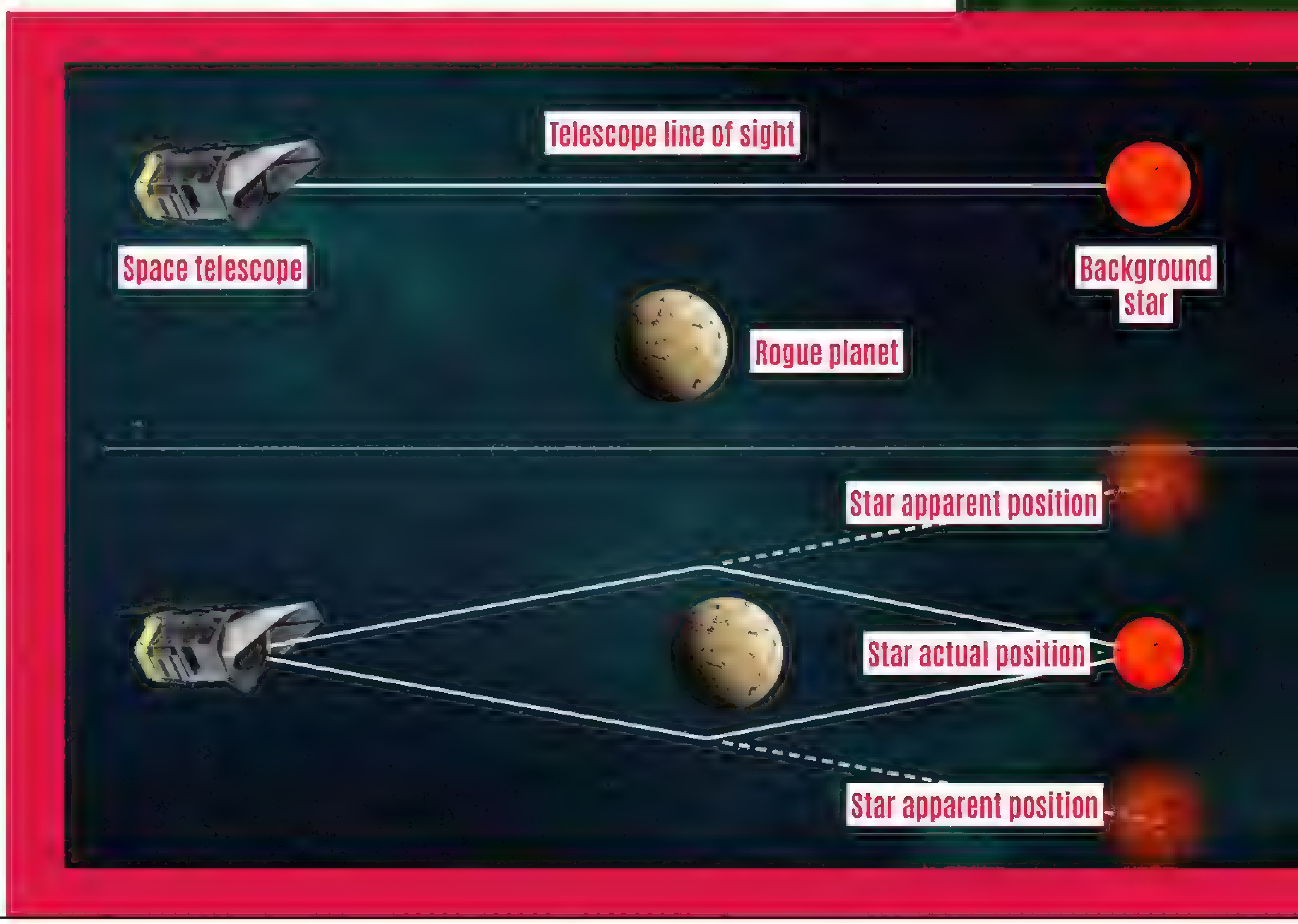
However, more recent research questions whether JuMBOs even exist. What is known for certain, though, is that humanity still has a lot more to learn about the planetary population of our home galaxy.

planetary system can also lead to the ejection of low-mass planets.

Exoplanets are usually spotted because of their effects on their parent stars. For example, an exoplanet that crosses the face of its star will cause a tiny and brief drop in that star's light output. Alternatively, the gravitational tug of a planet on its star can create a tiny wobble in the star that can also be seen in its light output. The fact that rogue planets have been orphaned from their stellar parents or never had them to begin with means that they can't be detected by the effects they have on a close star. This has made these free-floating worlds highly tricky to pin down.

Larger rogues around the size of Jupiter have been imaged directly thanks to the small amount of infrared light they emit, but smaller planets that freeze as a result of their lack of heat from a star and their lack of internal heat can't be seen in this way. Fortunately, when these orphan planets pass background stars, they can trigger an effect that emerges from Albert Einstein's theory of general relativity, called gravitational microlensing. "I work on gravitational microlensing, which is a technique to find exoplanets. It has the advantage over other methods [in] that it doesn't require detecting light from the planet or even the host star," Gaudi says. "In principle, it could detect free-floating planets with quite low masses. It's really the only way of detecting very low-mass planets that are not bound to their host star."

General relativity says that objects with mass cause a warping of the very fabric of space. As light passes this warp, it's curved. That means when a massive object comes between Earth and a background object and acts as a gravitational lens, the path of light from the object is curved. This has the effect of making the



> "Rogue planets provide a way of measuring how chaotic and violent planet formation might be"
> **Scott Gaudi**

An interstellar molecular gas cloud called Cepheus B. These clouds normally collapse to form stars, but small patches could birth rogue planets or brown dwarfs

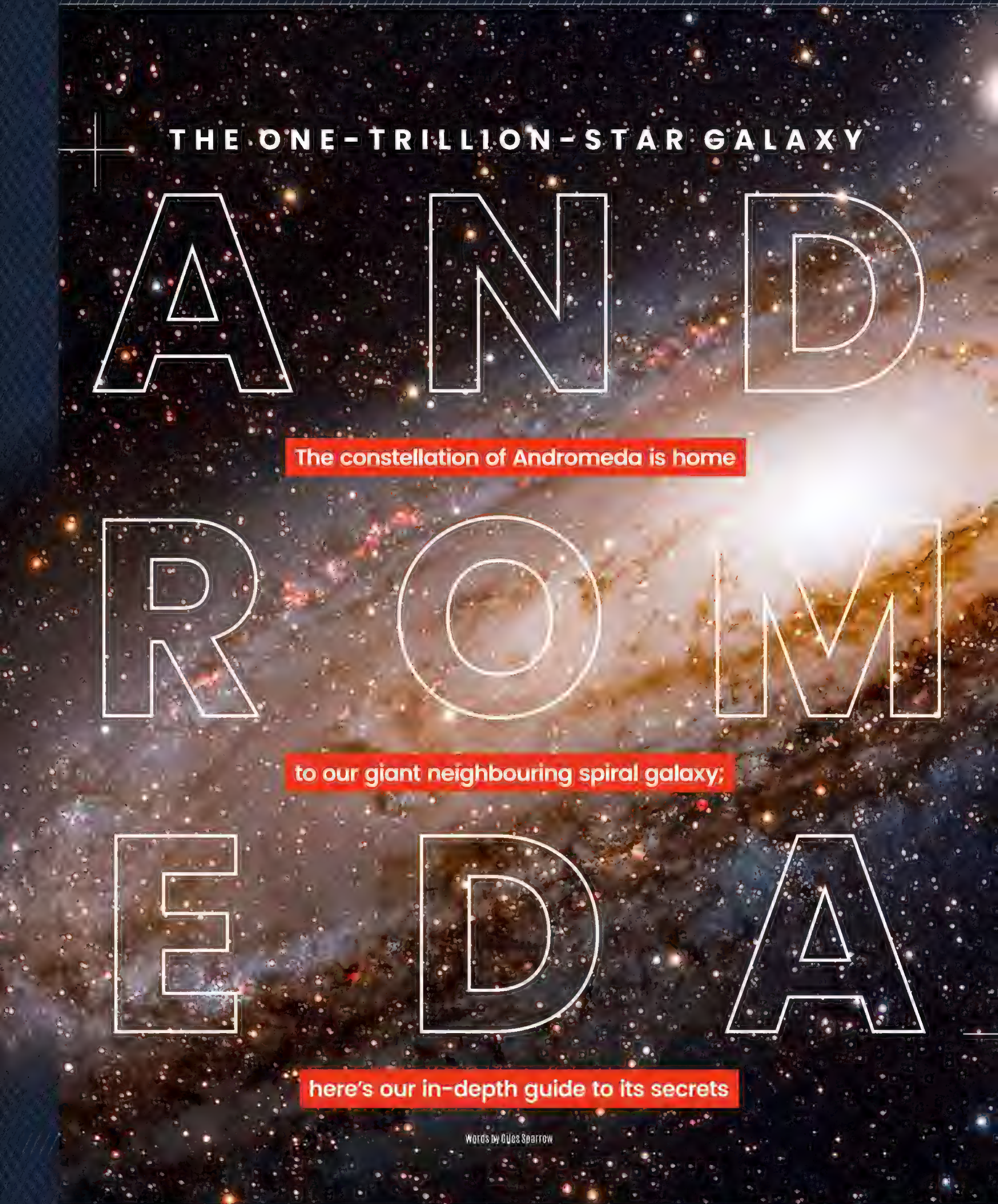
An illustration showing the gravitational lensing effect of a rogue planet passing in front of a background star

background object adopt a new apparent position in the sky. As the closer light passes to a gravitational lens, the more it's curved. An intervening object can cause the arrival time of light from the same object to vary, which can cause a background object to appear in multiple places in the same image. The catch is that the greater the mass of an intervening object, the more extreme the curvature of space it generates. That means while entire galaxies acting as a gravitational lens cause a huge amount of curvature and a large shift in apparent position, the effect of a planet with a mass around that of Earth is insignificantly smaller and can't be seen by looking at a single background star. It can be calculated, however, by looking at millions of stars and averaging the effect across them.

Both Johnson and Gaudi are heavily involved with the Nancy Grace Roman Space Telescope, which promises to have a massive impact on our knowledge of rogue planets when it launches in 2027, possibly even late-2026. The space telescope will do this by staring at millions of stars in the Milky Way to conduct a vast microlensing survey sensitive to relatively low-mass free-floating planets. "This is the next large astrophysics mission to be launched by NASA, and it will conduct a microlensing survey to search for planets," Gaudi says. "We estimate it will find around 1,500 bound exoplanets, but it'll also find hundreds of free-floating planets with masses all the way down to the mass of Mars – maybe even lower if rogue planets of lower mass are quite common."

Scientists are currently predicting that Roman will be able to spot a staggering 400 Earth-mass rogue planets in the Milky Way, massively boosting our understanding of these cosmic orphans. "I think there's still a lot to learn about rogue planets," Johnson concludes. "Being able to tie down the occurrence rate of these objects is going to lead to some big surprises."

Robert Lea
Space science writer
Rob is a science writer with a degree in physics and astronomy. He specialises in physics, astronomy, astrophysics and quantum physics.



THE ONE-TRILLION-STAR GALAXY

ANDROMEDA

The constellation of Andromeda is home to our giant neighbouring spiral galaxy; here's our in-depth guide to its secrets

Words by Giles Sparrow

THE MOST DISTANT LIGHT IN THE SKY

The Andromeda Galaxy is the most distant object we can see with the naked eye. Even on the darkest night, all the individual stars we can see are part of our home galaxy, the Milky Way. Just three naked-eye objects lie beyond its boundaries – two small satellite galaxies, the Large and Small Magellanic Cloud, visible only from the far-southern skies, and an oval patch of light in the northern constellation of Andromeda. Catalogued as Messier 31, it's easy to spot on moonless nights, and is best seen in the mid-evening sky around October to December.

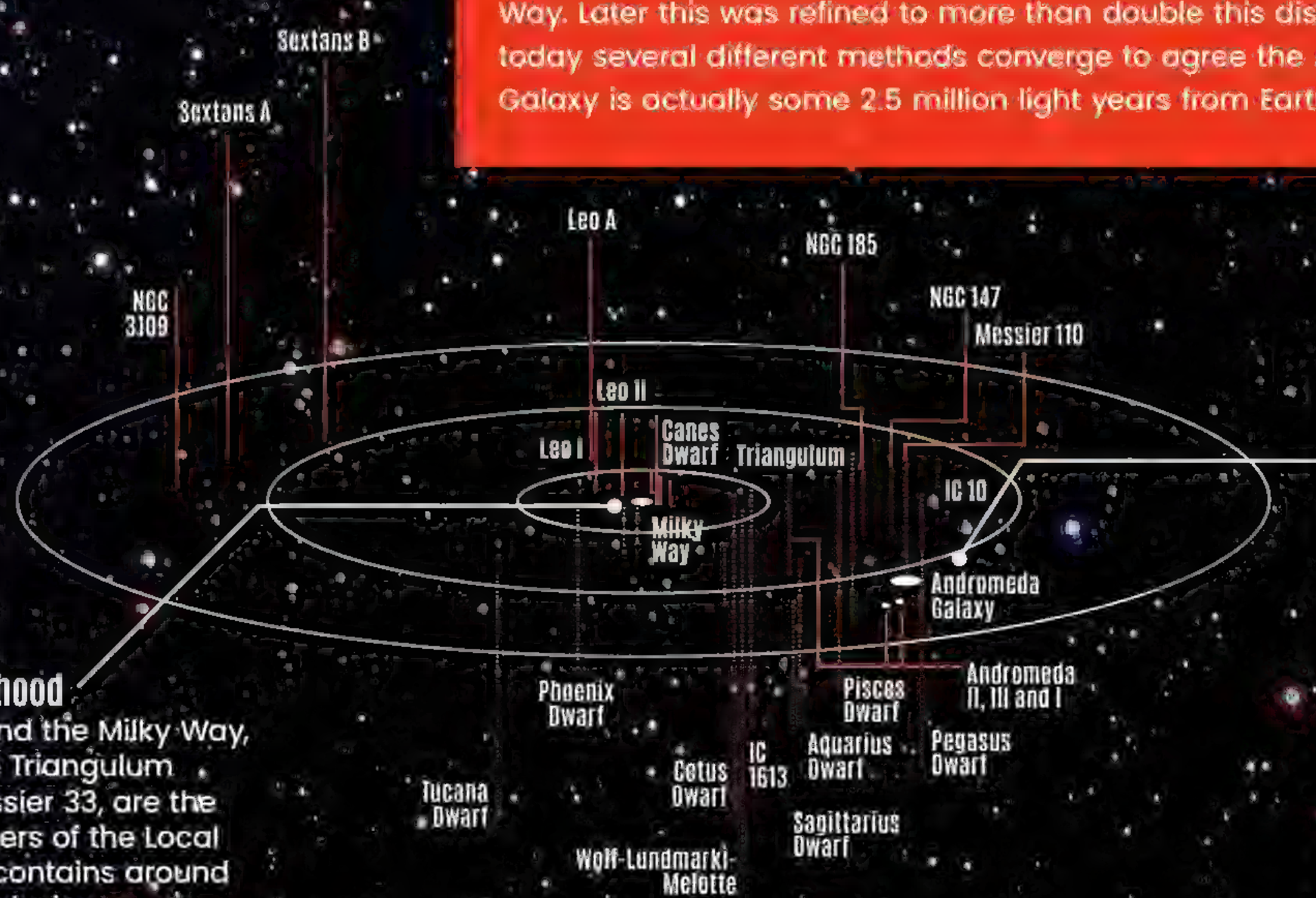
The constellation of Andromeda comprises two diverging chains of stars, linked at their base by the bright star Alpheratz on the northeastern corner of the distinctive Square of Pegasus. An imagined line between the second stars of each chain – the bright Mirach, or Beta Andromedae, and the fainter Mu Andromedae – leads northwards to Messier 31, appearing as a fuzzy 'star' of moderate brightness. Binoculars or telescopes with low magnification will reveal the fuzzy oval of its nucleus, and in dark skies you may also detect the faint glow of its outlying regions. Messier 31 appears six times wider than a full Moon.

"It's best seen in the mid-evening sky around October to December"

DEBATED DISTANCE

The starry nature of Messier 31 and many of the sky's other fuzzy celestial objects were first recognised around the turn of the 20th century. Andromeda was among the finest so-called 'spiral nebulae', but the true nature and location of these objects remained uncertain. Around 1912, US astronomer Vesto Slipher discovered that spiral nebulae were moving at speeds much faster than any known star, and were therefore probably independent of the Milky Way, but the argument was only settled through the work of Edwin Hubble and Milton Humason, unveiled in 1924. They identified Cepheid variables – stars with regular pulsations in a period linked to their luminosity – in several spiral nebulae. Hubble was then able to work out the distance to these stars based on their apparent brightness as seen from Earth. From measurements of a dozen Cepheids in Messier 31, he put its distance at 930,000 light years – far beyond the bounds of the Milky Way. Later this was refined to more than double this distance, and today several different methods converge to agree the Andromeda Galaxy is actually some 2.5 million light years from Earth.

WHERE IS IT?



Our neighbourhood
Andromeda and the Milky Way, along with the Triangulum Galaxy, or Messier 33, are the largest members of the Local Group, which contains around three dozen galaxies.

Collision course
Andromeda and the Milky Way are speeding towards each other at 400,000 kilometres (248 miles) per hour. There's also evidence that Andromeda and the Triangulum Galaxy interacted in the past.

Source: Wikipedia Commons © David (Deddy) Dayag

ANDROMEDA BASICS

Messier 31 is a spiral galaxy similar to our own Milky Way. It's a vast disc of stars, gas and dust orbiting around a bulging central hub where stars are most densely packed together. The entire galaxy is oriented at an angle of about 77 degrees, so rather than seeing it face-on or edge-on, we look across the disc at a shallow angle. This happens to concentrate the faint combined light from Andromeda's many billions of stars in a smaller region of the sky and make it easier to see. Long-exposure images capture the outlines of dark dust clouds silhouetted against the background glow of the galaxy's stars, and brighter blue-white patches within the disc indicate concentrations of brilliant high-mass young stars in recently formed star clusters. The hub, meanwhile, glows with the combined light of many billions of faint red and yellow stars, increasingly densely packed towards the very centre of the galaxy.

Our neighbour Andromeda is a barred spiral like the Milky Way

EXTENDED HALO

A large, roughly spherical region surrounding Andromeda is known as its halo. It contains stars in distant and eccentric orbits around Andromeda's hub, as well as at least 460 ball-shaped globular star clusters – three times more than those known around the Milky Way. Most of these clusters are relics from huge bursts of star formation that took place during the galactic collisions that helped Andromeda grow to its present size, but unlike the Milky Way globulars – which all seem to be around 12 billion years old – they show a range of ages. The particularly massive clusters Mayall II and B023-G78 probably have a different origin, and may be the stripped-down cores of cannibalised galaxies.

Most of the wandering stars in Andromeda's halo are said to be 'metal-poor'. They are made almost entirely of hydrogen and helium, with few of the heavier elements created and distributed during the life cycles of stars. This indicates an extremely ancient origin, though in contrast one distinct stream of 'metal-rich' younger stars runs through them. One final component of the halo is a vast cloud of hot gas roughly 2 million light years across. Stretching halfway to the Milky Way, this gas is rich in heavy elements and has half the mass of all Messier 31's stars.

WHAT WE KNOW ABOUT ANDROMEDA

A cloud of stars

In 1864, photographic pioneer William Huggins collected light from Andromeda and other nebulae and split it into rainbow-like spectra. This showed that Messier 31 was a concentrated group of stars rather than a cloud of interstellar gas.
William Huggins' private observatory, Tulse Hill, London

A spiral 'nebula'

Hubble took its catalogue number, Messier 31, from French astronomer Charles Messier, who listed star clusters and cloud-like nebulae in his catalogue of 1771. In 1850, astronomer William Parsons used his giant telescope to sketch Andromeda's shape.
The Great Leviathan telescope at Birr Castle, Ireland

Approaching Earth

The compression of Andromeda's starlight confirmed the galaxy's motion towards us as early as 1912, even before it was known to be an independent galaxy.
The Clark Refractor at Lowell Observatory, Arizona

Double core

In 1993, astronomers discovered that Andromeda's central core has two distinct concentrations of stars. The odd appearance is now thought to be a result of stars jostling together in certain regions as they orbit the galaxy's central black hole.
Hubble Space Telescope

Bound for collision

In 2012, astronomers announced the results of a decade-long effort to measure Andromeda's lateral (sideways) motion in the sky, confirming that it is not enough to avoid the Milky Way and our two galaxies are doomed to collide.
Hubble Space Telescope

A galaxy beyond our own

In 1925, Edwin Hubble identified Cepheid variable stars in images of Andromeda – a type of star whose variations indicate its true brightness. This revealed Andromeda's true, enormous distance, and that Messier 31 is a galaxy in its own right.
Hooker Telescope at Mount Wilson Observatory, California

VIEWING OUR GALACTIC NEIGHBOUR

1 Ancient core The halo and bulge of a spiral galaxy contain its oldest stars.

2 An old face This Spitzer image shows Andromeda's older population of stars.

3 Ring galaxy Messier 31 seen in ultraviolet. With the glare gone, it shows hot young stars.

4 Dusty galaxy Dark dust lanes line dense clouds of gas where star formation is actively taking place.

5 Old and young This false-colour composite image reveals the ring structure of the galaxy's disc and the populations of old and young stars.

6 Hot and cold The hottest stars (blue) are also the most massive and youngest, whereas older stars (green) are less massive and cooler.

Spitzer Space Telescope
Launch date: 2003
Mission: NASA's Spitzer observed the universe in infrared wavelengths, which can penetrate through interstellar dust clouds.

Galaxy Evolution Explorer (GALEX)
Launch date: 2003
Mission: This ultraviolet space telescope was designed to study the structure and evolution of galaxies by observing their stars.

ANDROMEDA'S STARS

While the Andromeda Galaxy was once thought to be significantly more massive than the Milky Way, newer calculations have produced lower estimates for Andromeda's mass and higher ones for our own galaxy, suggesting it's the other way around. The new figures put Andromeda's mass at between 800 billion and 1.1 trillion Suns. Stars account for roughly ten to 15 per cent of this, and analysis of their combined light indicates 30 per cent of this stellar mass is concentrated in the central hub region, with 56 per cent scattered across the disc. The remainder is in a broad but sparsely populated halo around the galaxy.

> "The new figures put Andromeda's mass at between 800 billion and 1.1 trillion Suns"

Most of Andromeda's individual stars seem to be comparatively old, red and dim compared to those of the Milky Way, with stars of at least 7 billion years old dominating even in the star-forming disc region. Red stars have lower masses than the Sun, and while numbers are hard to pin down due to factors such as interstellar dust, some estimates put Andromeda's total population at about a trillion, compared to the Milky Way's 100 to 400 billion stars with a higher average mass. If both galaxies were seen from outside, Andromeda would appear at least 75 per cent brighter than our galaxy.

SPIRAL STRUCTURE

Knowing Andromeda's true distance, astronomers can determine its dimensions based on the falloff of starlight from its centre to its edges. This method gives the galaxy's main disc a diameter of about 152,000 light years – roughly 50 per cent larger than the Milky Way. Stars, gas and dust in the disc orbit on roughly circular paths. Their speed varies with their distance from the centre, but they also move more slowly in certain regions than in others, creating a spiral pattern of stellar traffic jams where new star formation is also triggered by the compression of gas and dust.

Andromeda's shallow angle to Earth hides much of the detail from view, but most astronomers agree there are two main spiral arms. However, the rate of star formation within them is only about one-fifth of that in our own galaxy. Infrared telescopes can trace more detail by peering through the countless stars to see the galaxy's 'skeleton' of interstellar dust. Their images complicate the story, showing a dense ring of dust in a ring about 32,000 light years from the core, coinciding with the most concentrated starbirth. They also reveal that the arms are rooted at the ends of a bar-like structure, making Andromeda, like the Milky Way, a barred spiral.

1 Telltale dust ring
Examination of Andromeda in the infrared reveals a dusty inner ring believed to have been caused by Messier 32 ripping straight through its disc more than 200 million years ago.

2 Winding arms
Wound up in a clockwise direction, Messier 31's spiral arms are outlined by low-density clouds of partially ionised gas where young, hot, blue stars have recently formed.

3 Dust and gas
Cold dust and gas is arranged into overlapping rings according to an infrared to ultraviolet view, causing astronomers to believe that Andromeda may be transforming into a ring galaxy.

4 Brilliantly bright double nucleus
Messier 31's inner nuclei, which are separated by 4.9 light years, consist of compact discs of hot, A-class stars. One concentration is brighter than the other.

5 S-shaped disc
Inclined at roughly 77 degrees relative to Earth, Andromeda has a strange warped disc in the shape of an 'S', possibly caused by the gravitational interaction of satellite galaxies.

6 A 'misleading' bulge
In visible light, you wouldn't think that a bar streaks through Andromeda's centre. It only becomes apparent when you look at this section of the galaxy in infrared.

INTO THE HUB

Towards the centre of Andromeda, stars become increasingly concentrated, and a rapid increase in their orbital speeds within the innermost few light years indicates they are orbiting a huge central compact mass. This is now known to be a supermassive black hole with a mass of at least 100 million Suns.

However, detailed images of the hub reveal another puzzle. Messier 31's innermost stars form not one but two clumps – a brighter, larger red one and a somewhat fainter one with a blue tint. The fainter one corresponds to the galaxy's true centre – a region of active star formation producing young, short-lived blue stars near the black hole. But what is the brighter one? An early idea was that it might represent the surviving core of a smaller galaxy cannibalised by Andromeda, but later studies revealed that it is in fact a 'traffic jam' of older stars in an offset elliptical disc that surrounds the black hole at greater distance. As these stars reach the outer edge of their orbits, they naturally slow down and appear clumped together. The existence of the disc itself, however, may be evidence of just such a galactic merger in Andromeda's past.

RECENT TRAUMA

Messier 31 originally coalesced in a series of mergers between smaller galaxies, each of which triggered new generations of starbirth. Andromeda continued to grow by occasionally cannibalising its much smaller neighbours, but around 2 to 3 billion years ago it underwent a traumatic collision with a relatively large galaxy with roughly a quarter of its own mass. This triggered a violent wave of star formation. Interstellar gas clouds were rammed together, heating them to a point where they boiled away into the halo. They were further enriched with heavy elements ejected from the disc as the most massive and short-lived stars created by the starburst destroyed themselves in spectacular supernova explosions. The central black holes of the two galaxies spiralled together and merged, perhaps generating a gravitational 'recoil' that left the final black hole wobbling and generated the offset stellar disc seen in Andromeda's nucleus today. In the aftermath of the merger, the galaxy's spiral structure eventually recovered, but its rate of ongoing starbirth was greatly reduced.

7 Heavyweight supermassive black hole

Nestled at the centre lies an ultraluminous X-ray-belching supermassive black hole that's significantly larger than the Milky Way's at up to 230 million solar masses.

8 'Jumping' stars and clusters

Stars found in the galaxy's halo and globular clusters may 'jump' high above the disc before diving back in again, popping out the bottom of the galaxy before starting the cycle again.

9 Staying and moving

Stars found in Andromeda's disc are influenced by gravity and generally stay where they are, occasionally bobbing up and down as they orbit the galactic centre.

10 Alternating speeds

Stars near the galactic centre move quickest, with speed decreasing the further out stars orbit. At around 80,000 light years the speed becomes constant, suggesting the presence of dark matter.

FROM THE SIDE

Globular clusters

The stellar halo is home to groups of stars called globular clusters. The largest around Messier 31 is called Mayall II. It's twice as big as the Milky Way's largest.

Bulging out

The reason for the bulge's name is clear when the galaxy is viewed from the side. It hides a huge black hole, much heavier than the Milky Way's.

Thick and thin

The discs are divided into 'thick' and 'thin'. The thick disc contains stars over 8 billion years old, while a thinner disc houses younger stars.

Gas and dust

The spiral disc is filled with gas and dust. Dust is produced by dying stars and recycled into new stars born in nebulous regions of gas.

DARK MATTER LABORATORY

As with most galaxies, Andromeda's visible stars, dust and hot gas only tell part of its story – all of the galaxy's detectable material is vastly outweighed by invisible 'dark matter' that is both dark and effectively transparent. Dark matter may account for about 80 to 85 per cent of Andromeda's overall mass, and measurements of the galaxy's rotation curve – the speeds of stars orbiting at different distances from its centre – indicate that while some of this concentrates around the core, most lies beyond the visible disc, spread across a similar volume to the hot gas halo.

Messier 31's closeness to Earth and large size in the sky make it a unique laboratory for testing theories about dark matter and its possible properties. For instance, the abundance of stars in the disc should permit future surveys looking for brief eclipses caused by MAssive Compact Halo Objects (MACHOs) – small, dark objects such as rogue planets, black holes and burnt-out stars that could contribute to the 'missing' mass. Even more intriguing, some astronomers suggest that unexplained emissions of high-energy gamma rays from Andromeda's core and halo might indicate the decay of dark matter particles into forms that interact with normal matter, perhaps finally producing an observable 'signature' for this elusive material.

SATELLITE GALAXIES

Andromeda has a family of satellite galaxies. The brightest and best known are Messier 32 and Messier 110, but there are more than two dozen other fainter objects, mostly in more distant orbits. The majority of these smaller satellites are classed as dwarf ellipticals and dwarf spheroidals – small, loose balls of ancient stars whose low contrast makes them very hard to detect. Intriguingly, many orbit in a common plane around Andromeda, perhaps suggesting a shared origin. Messier 32 is the prototype for a rare class known as compact ellipticals, which pack a large number of stars into a relatively small space. A central black hole of between 1.5 and 5 million solar masses may have helped hold it together against powerful tidal forces when it passed directly through Andromeda some 210 million years ago. Some have suggested that Messier 32 may even be the surviving core of a much larger galaxy that seems to have collided with Andromeda 2 to 3 billion years ago.

THE LOCAL GROUP

Together, the Milky Way and Andromeda extend their gravitational influence over a region of space roughly 10 million light years across, holding together a family of several dozen galaxies known as the Local Group. Many Local Group members are direct satellites of the two major galaxies, but there are also more loosely bound outliers, including the Triangulum Galaxy, or Messier 33, a somewhat smaller but still substantial spiral galaxy lying fairly close to Andromeda.

Within the local group, gravitational attraction between galaxies overcomes the broader effects of cosmic expansion that drive them apart on the larger scale. Hence Andromeda and the Milky Way are approaching one another at a speed of about 110 kilometres (68 miles) per second. Four to 5 billion years from now, they could collide in a spectacular event. If this happens, collisions between individual stars will be unlikely, but many will have their orbits disrupted as they are flung off into intergalactic space. Huge bursts of star formation will be triggered as gas clouds from the two galaxies are rammed together, while over hundreds of millions of years their central black holes will spiral around each other before merging. The ultimate form of the merged galaxy, sometimes nicknamed 'Milkomeda', will depend on how much star-forming gas survives the process.

The SMC and LMC alongside the Milky Way

FOCUS ON

ONE OF THE CLOSEST GALAXIES TO THE MILKY WAY MAY BE HIDING A SECOND GALAXY

New observations of the Small Magellanic Cloud show that it might actually be two galaxies disguised as one

Reported by Robert Lea

The Small Magellanic Cloud (SMC) is a nearby galaxy that's very familiar to astronomers, or so they thought. New research suggests that the satellite galaxy of the Milky Way, located around 199,000 light years from Earth, seems to have been hiding a secret – it's actually two galaxies, one behind the other. To make the discovery, a team led by Claire Murray, an astronomer at the Space Telescope Science Institute in Maryland, tracked the movement of gas clouds and young stars being born within them around the SMC. They found that the small galaxy, which is around 18,900 light years wide – less than one-fifth the width of the Milky Way – contains two distinct stellar nurseries thousands of light years apart. Both the SMC and the Large Magellanic Cloud (LMC) are dwarf galaxies that are gravitationally bound to the Milky Way and are being steadily drawn towards our galaxy for a collision and merger in the far future.

While the LMC exhibits a disc-like shape similar to that of the Milky Way, the SMC is more irregular. The SMC has only one-third the mass of the larger dwarf galaxy, which has a mass equivalent to around 7 billion times that of the Sun. Although the SMC was previously thought to consist of multiple components, it's somewhat obscured by interstellar clouds of gas and dust, meaning these features have been hard to distinguish.

Murray has previously determined that the SMC is a 'train wreck' of a dwarf galaxy, full of gas disrupted by gravitational interactions with the Milky Way and the LMC. For the new investigation of the SMC, Murray and her colleagues zoomed in on radio waves emitted by hydrogen gas in the dwarf galaxy using the Australian Square Kilometre Array Pathfinder radio telescope, which comprises 36 dish antennae. The team then followed up these observations by using the European Space Agency's (ESA) Gaia spacecraft – which was being used to create a 3D map of stars in the Milky Way – to track the speed and direction of thousands of stars in the SMC that were younger than 10 million years old.

Working with the assumption that these young stars are moving in conjunction with the large clouds of gas that birthed them, the researchers spotted two distinct star-birthing patches of gas and dust. The two clouds have different abundances of metals, meaning elements heavier than hydrogen or helium, and one cloud seems to be more distant from Earth than the other, though their exact separation isn't yet clear.

SPACE SCIENCE

Telescopes and space missions help us better understand the cosmos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20 GREATEST WOMEN IN SPACE

The groundbreaking heroes who have changed our understanding of the universe

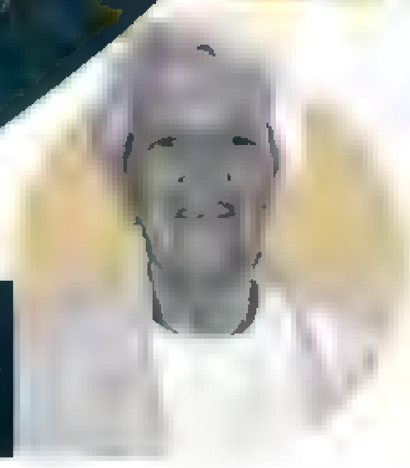
Our knowledge of space has burgeoned since the 1800s, and women have played a vital role in expanding our consciousness. Yet the contributions of these women have often been downplayed or outright excised from history. The inspiring scientists on this list, along with their female and female-identifying colleagues, have faced and overcome scorn, prejudice and injustice simply for their love of science and the quest to know more about the cosmos. Browsing the names that follow, you'll find that women are responsible for some of the most crucial discoveries and developments in space science. This may be the first time you encounter these names, though the things we learned through them will be familiar. This list doesn't just focus on the past and the women who have brought us to where we are today – it also honours the women who are pushing forward, fighting for equality and demolishing the barriers they, and those that preceded them, face.

1 VALENTINA TERESHKOVA

Tereshkova is a Russian engineer and former Soviet cosmonaut. On 16 June 1963 at the height of the Space Race, Tereshkova became the first woman to journey to space as she embarked on a solo mission in the Vostok 6 spacecraft (inset). She spent around three days in space, orbiting Earth 48 times. A former textile worker who found her way into the Cosmonaut Corps space program because of her amateur skydiving experience, Tereshkova stuck around after the dissolution of the first group of female cosmonauts in 1969, instructing future cosmonauts. When her space days were over, Tereshkova enjoyed a successful career in Russian politics, holding several important political offices and serving in the national State Duma as recently as 2021.

"Women are responsible for some of the most crucial discoveries and developments in space science"

2 VERA C RUBIN



Vera Rubin was the American astronomer who discovered that some galaxies are rotating so fast that if their visible matter was the only mass they possessed, they should fly apart. This led scientists to posit the existence of dark matter, a form of matter that doesn't interact with light.

Dark matter has since been calculated to account for about 85 per cent of the matter in the universe, meaning all the things we can see – the stars, planets, moons, all the cosmic dust and gas and all living things, including us – account for just 15 per cent of the 'stuff' in the cosmos. Its discovery by Rubin marks one of the most significant shifts in the history of cosmology.

"Rubin is a pioneer for me as a cosmologist. Her exhaustive observational work, recording and measuring the velocity of stars inside galaxies, was fundamental to developing the concept of dark matter and its importance in shaping galaxies," Luz Ángela García Peñaloza, a cosmologist at Universidad ECCI in Columbia, told **All About Space** magazine. "I think she deserves the recognition the community has granted her by renaming the Large Synoptic Survey Telescope [...] after her."

Rubin, who earned her master's degree in 1951 at Cornell, became the second woman to be elected to the National Academy of Sciences in 1981. In 1993 she was awarded the National Medal of Science. In addition to her work in cosmology, Rubin not only overcame a wealth of gender barriers in science herself but also inspired and encouraged other women to pursue academic careers in what were then typically male-dominated fields.

3 CECILIA PAYNE-GAPOSCHKIN

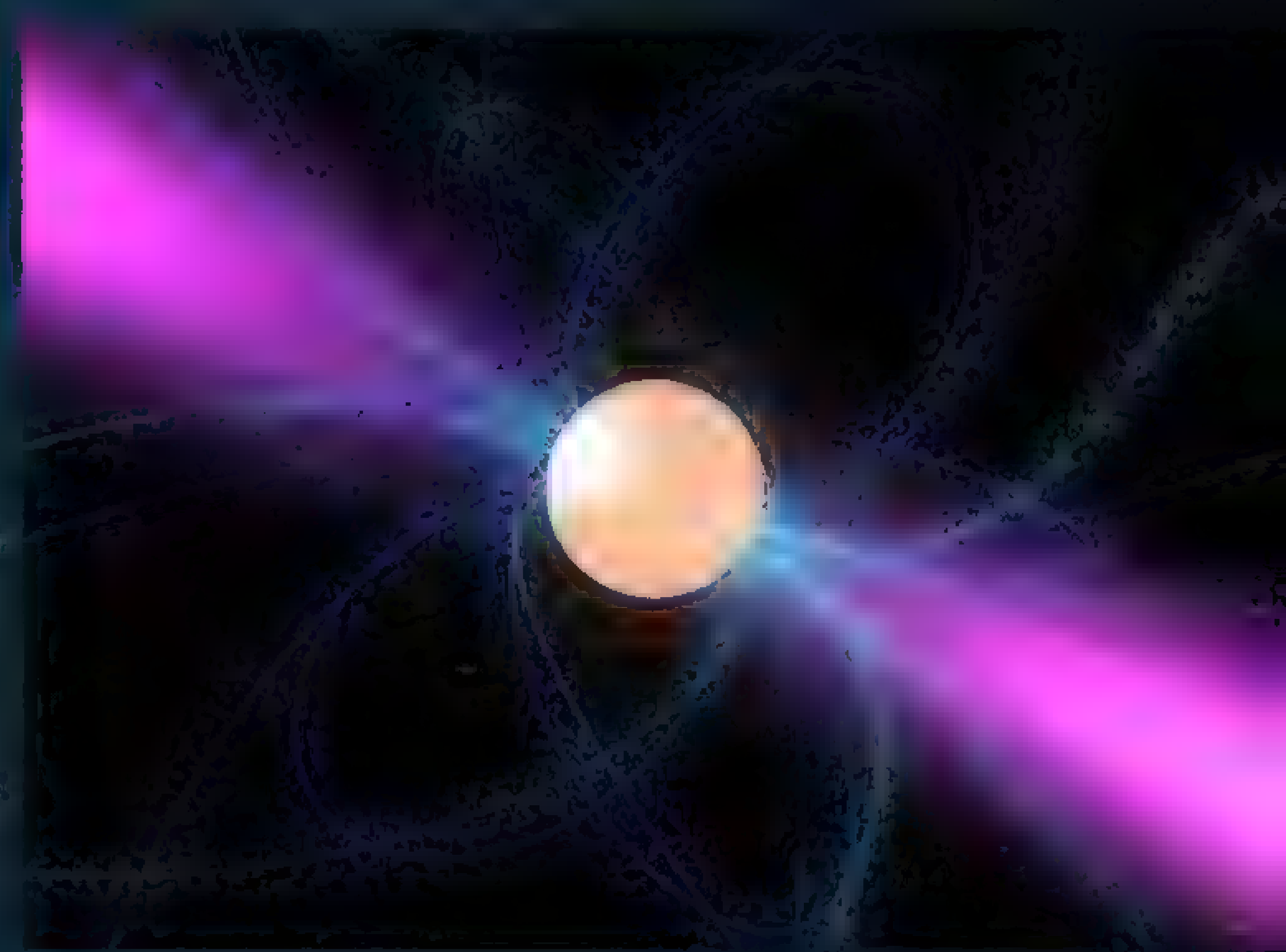
Payne-Gaposchkin was a British-born American astronomer who radically developed our understanding of the Sun and other stars. Not only did Payne-Gaposchkin find that the stars are mostly composed of hydrogen and helium, the universe's two lightest elements, she also established that it's possible to classify different stars using their temperatures. Astronomer Henry Norris Russell dissuaded Payne-Gaposchkin from publishing her conclusion about the Sun's material composition, as he thought it was made of the same material that comprises Earth. In 1925, he chided Payne-Gaposchkin, telling her it was clearly impossible for hydrogen to be so abundant in the cosmos. Russell was forced to acknowledge he was wrong and Payne-Gaposchkin was proven right in 1929 when he himself published research that suggested the dominance of hydrogen in the Sun and other stars. Though Russell acknowledged Payne-Gaposchkin's 1925 work on the topic, he failed to mention he had rejected the idea half a decade previously.

4 JOCELYN BELL BURNELL

Bell Burnell discovered the first radio pulsars in 1967. These sources of pulsed radio waves were later found to be rapidly spinning stellar remnants called neutron stars. Though this discovery earned Bell Burnell's supervisor, Antony Hewish, the Nobel Prize in Physics in 1974, she was not one of the recipients. Bell Burnell maintained that the prize was presented appropriately given her student status at the time of the discovery, despite understandable outrage in the scientific community regarding her omission.

"Bell Burnell, to me, is an outstanding figure in astrophysics. The discovery of pulsars in the late 1960s and subsequent work in the field have been fundamental to unveiling and developing radio astronomy," García Peñaloza says. "Although she was not awarded the Nobel Prize, she has gotten multiple awards for her remarkable work, and she has returned a lot to the community by offering scholarships for women who want to study physics and astronomy."

Bell Burnell was made Commander of the Order of the British Empire (CBE) in 1999 and was made a dame in 2007. She became a member of the Royal Society in 2003 and served as president of the Royal Astronomical Society from 2002 to 2004, in addition to being elected president of the Institute of Physics for two terms in 2008. In 2018, Bell Burnell was awarded the Special Breakthrough Prize in Fundamental Physics. The prize money was used to create a fund that helps female, minority and refugee students become research physicists.



5 ANDREA GHEZ

Ghez is an American astrophysicist whose major contribution to science was the discovery that a supermassive black hole dwells at the centre of the Milky Way, our home galaxy. She arrived at this conclusion when looking at the stars at the heart of the Milky Way using a technique she had previously used to study binary star pairs. This showed the radio source Sagittarius A* (Sgr A*) to be an object with around 4 million times the mass of the Sun crammed into a region too small to be a stellar cluster. For the realisation that Sgr A* is a supermassive black hole, she won the 2020 Nobel Prize in Physics, sharing the award with British mathematician Roger Penrose and German astronomer Reinhard Genzel.

She was only the fourth woman to win the Nobel Prize in Physics, after Marie Curie in 1903, Maria Goeppert-Mayer in 1963 and Donna Strickland in 2018. "Ghez is a clear example of tenacity in astronomy. From the very beginning of her career she was devoted to understanding the supermassive objects in the centres of galaxies, to the point that she is the fourth woman to be awarded the Nobel Prize in physics," García Peñaloza says. "For me, she is an outstanding role model."

6

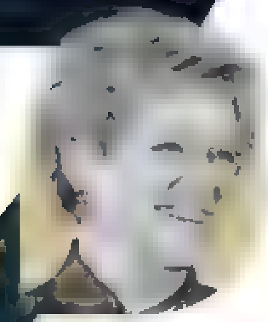
SARA SEAGER

Seager is a Canadian–American astronomer and planetary scientist who teaches at the Massachusetts Institute of Technology (MIT). She is renowned for her work on planets outside the Solar System and their atmospheres. The first exoplanets were discovered in the 1990s, and in the three decades since the known exoplanet catalogue has burgeoned to contain over 6,000 confirmed entries, with thousands more suspected planets awaiting confirmation. Working with NASA's Transiting Exoplanet Survey Satellite (TESS), Seager is placed at the cutting edge of this rapidly developing field.

Perhaps her finest discovery is finding a terrestrial exoplanet analogous to Earth. This effort to discover 'Earth's twin' means that in the future, when textbooks discussing the discovery of extraterrestrial life are published, there is a good chance Seager's name will be found within the pages.

7

SANDRA FABER



Faber is an American astrophysicist at the University of Santa Cruz and the Lick Observatory who is perhaps best known for her research on the evolution of galaxies. In 1979, Faber co-authored a paper with American astronomer John S Gallagher, gathering all the evidence to date in favour of dark matter. Following this, Faber produced research that suggested dark matter was not comprised of fast-moving or 'hot' neutrinos, but was instead composed of slow-moving or 'cold' particles that remained undiscovered, and still do to this day. As such, Faber was one of the pioneers of the cold dark matter model that serves as the favoured so-called standard model of cosmology today.

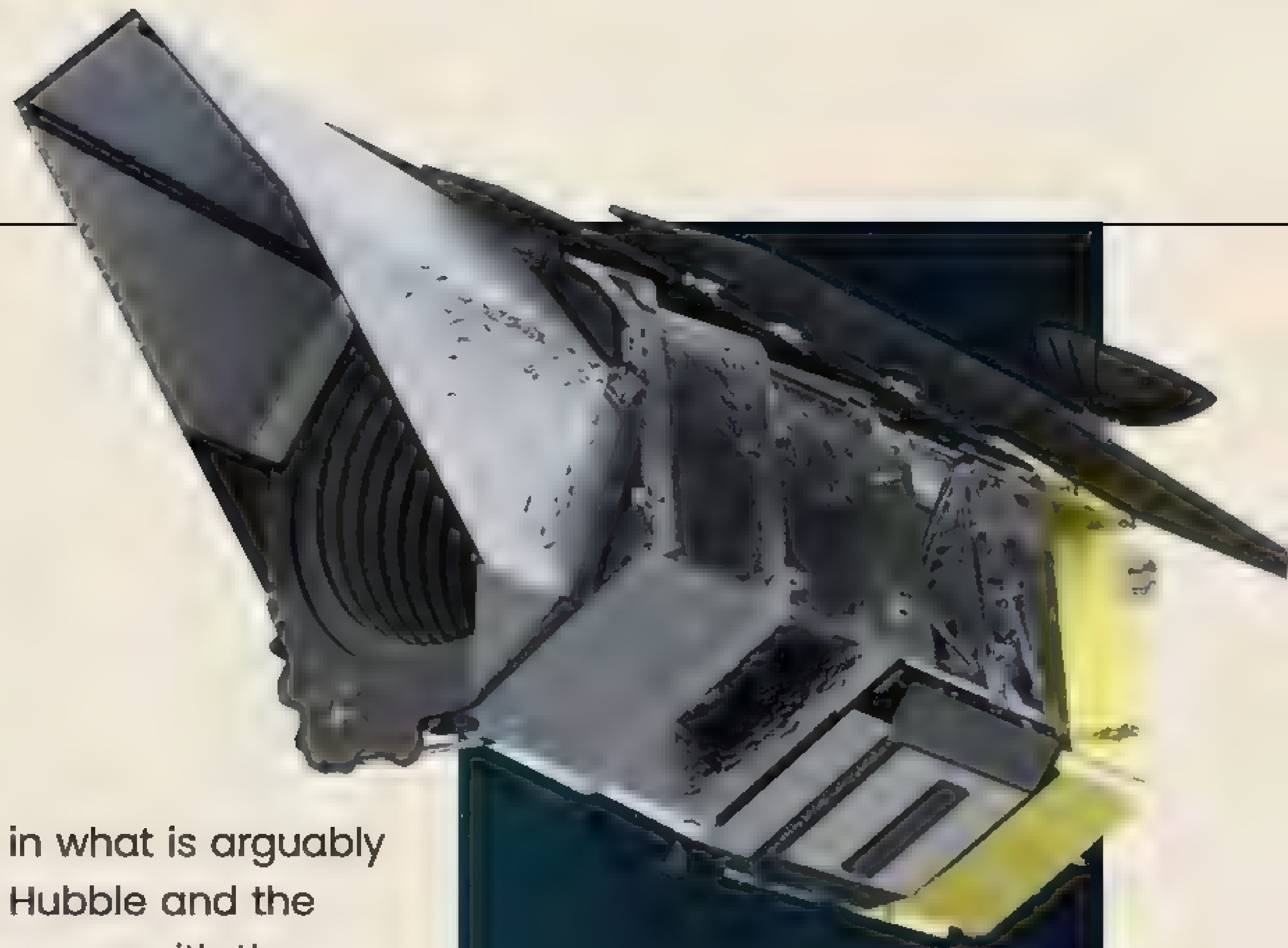
8

SALLY RIDE

A true trailblazer, Ride was a physicist and astronaut. On 18 June 1983, she became the first American woman and the third woman overall to journey into space. Ride was part of Space Shuttle Challenger's STS-7 mission, accompanied by four male crewmates. Following her own space adventures, she embarked on an award-winning academic career at the University of California, San Diego, and provided invaluable insight into space travel. This included serving as a member of the Challenger disaster investigation board with physicist Richard Feynman, after which she became the first director of NASA's Office of Exploration.

Ride received a wealth of honours and awards, including induction into the National Women's Hall of Fame, the California Hall of Fame, the Aviation Hall of Fame and the Astronaut Hall of Fame. She was awarded the NASA Space Flight Medal twice. In 2012, Ride was honoured with the National Space Grant Distinguished Service Award. Sadly, she passed away in the same year at the age of 61.

9 NANCY ROMAN



Roman was an American astronomer who became NASA's first chief of astronomy in 1959. She is often affectionately referred to as the 'Mother of Hubble', a nickname earned through Roman's tireless campaign to place a telescope in space, away from the interfering effects of Earth's atmosphere. When NASA began planning for the Hubble Space Telescope in 1979, Roman was at the forefront of preparations for this milestone in a new generation of versatile space telescopes. Hubble was launched in 1990 and is still delivering images and data to scientists that have transformed our understanding of the cosmos in fundamental ways.

"Roman is another unbelievably important figure in astronomy. Her contributions include research in stellar classification and dynamics," García Peñaloza says. "However, she probably had a bigger impact as a female role model, acting as the first female executive at NASA in the 1960s. In fact, the upcoming Wide-Field Infrared Survey Telescope has been renamed the Nancy Grace Roman Space Telescope after her."

Astronomy is currently in what is arguably its golden age thanks to Hubble and the James Webb Space Telescope, with the Roman telescope on the horizon. It is hard to imagine that space science could have reached these heights so soon without the 'Mother of Hubble'. Roman wasn't just an advocate of cutting-edge space telescopes, however. She was an equally strong advocate of efforts to encourage girls to pursue careers in science, thus becoming a role model for future generations and inspiring many to follow this career path.

"She probably had a bigger impact as a female role model, acting as the first female executive at NASA in the 1960s"

Luz Ángela García Peñaloza

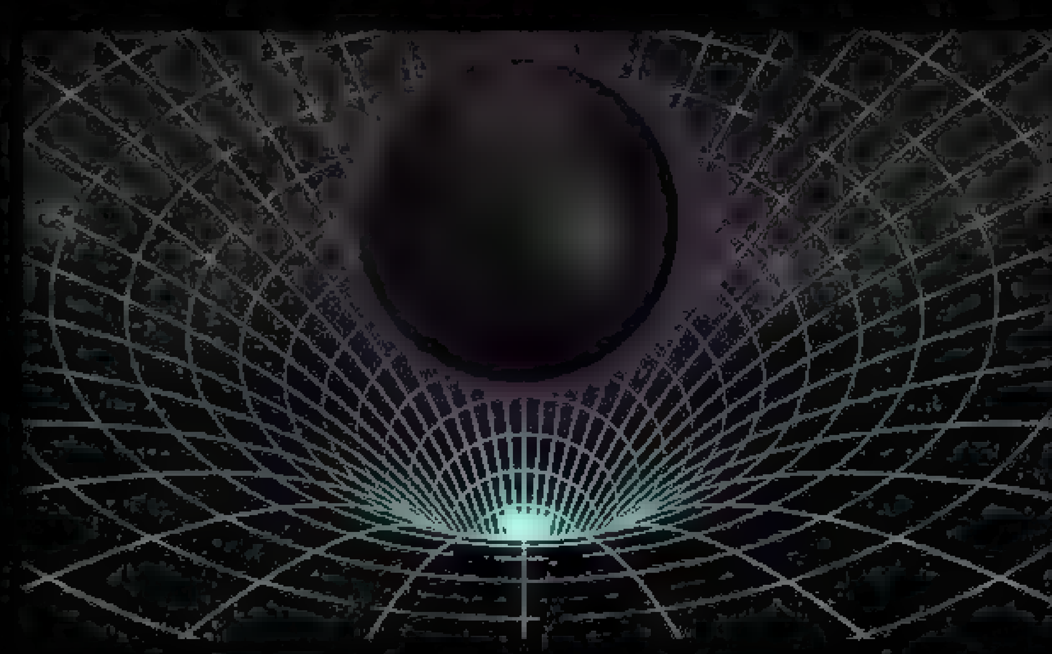
10 CAROLYN PORCO

This American planetary scientist began her work imaging the outer planets, deepening our knowledge of the outskirts of our planetary system as part of the Voyager team. Porco was integral to the study of Saturn's rings and moons with Cassini and in investigating Pluto and Kuiper Belt objects with the New Horizons spacecraft. Her work extends beyond the limits of the Solar System, too. Working with Voyager 1 (the first human-made craft to have journeyed beyond the edges of the Solar System) and Voyager 2, Porco has also been involved in studying the interstellar medium that lies between stars.

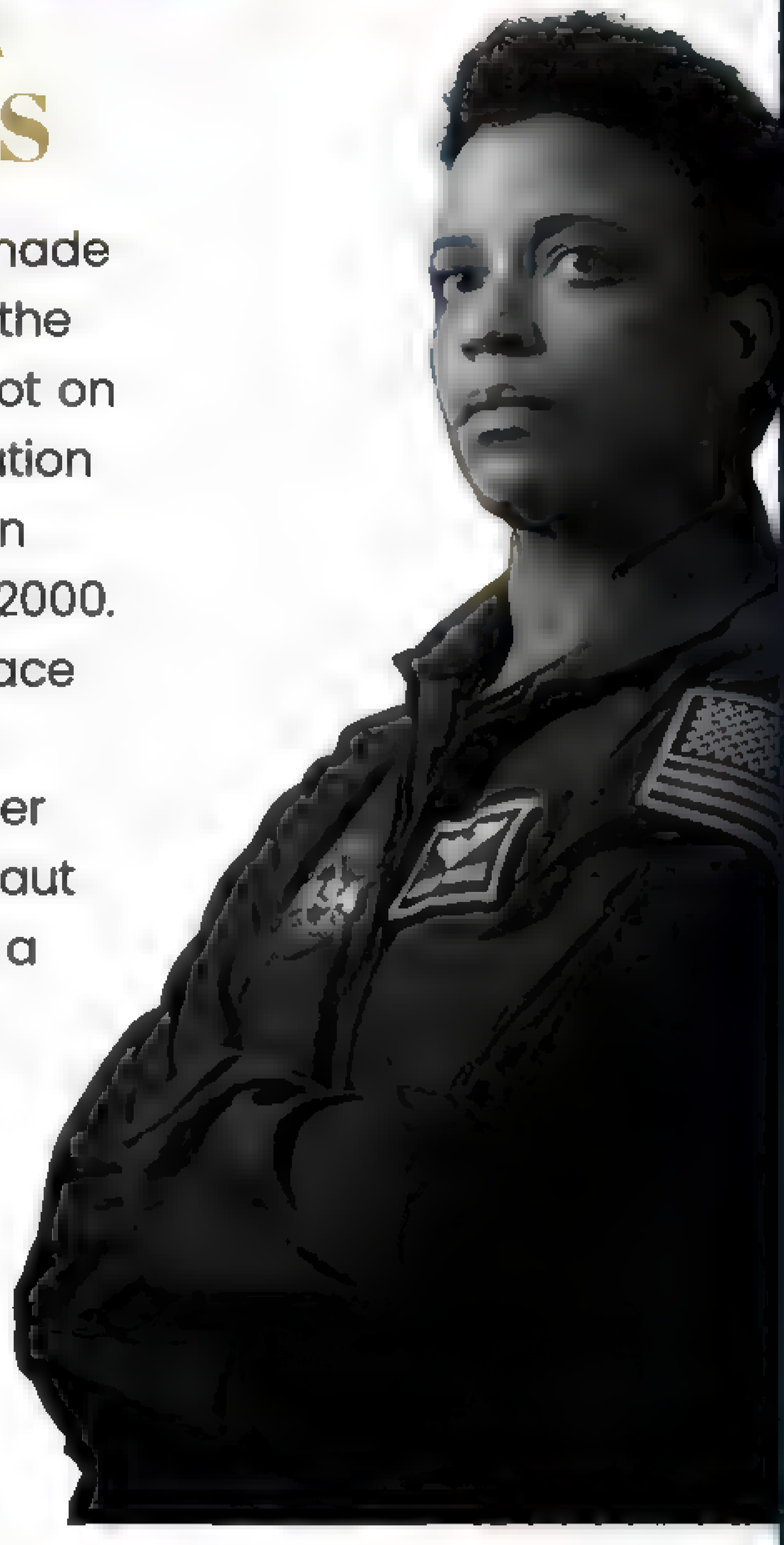
11 EMMY NOETHER

There aren't many who could have shocked Einstein with their latent understanding of the universe, but German mathematician Emmy Noether was certainly on that list. She was the woman who saved general relativity. Einstein introduced his theory of gravity in 1915, but this landmark theory wasn't without issues. For example, energy conservation laws seemed to break down in the curved space of general relativity. David Hilbert and Felix Klein, mathematicians at the University of Göttingen, had attempted to solve these issues, but failed. Hilbert brought Noether to Göttingen, believing that her mathematical background and experience with invariants could be useful in solving the challenges of general relativity. The development of Noether's first and second theorems introduced a symmetry to the universe that solved the issues with relativity and also created a new field of abstract algebra.

Despite her clear genius and aptitude, Noether had to overcome a wealth of challenges related to her gender to be allowed to attend lectures and classes. Today she is remembered by the Noether Lecture, which was established by the Association for Women in Mathematics in 1980 to honour women who have made substantial contributions to the mathematical sciences.



12 JESSICA WATKINS



On 27 April 2022, Watkins made history when she became the first Black woman to set foot on the International Space Station (ISS), which has had human residents since November 2000. This was the first trip to space for Watkins, who was born on 14 May 1988, following her selection as a NASA astronaut in 2017. Watkins, who holds a doctorate in geology from the University of California, Los Angeles, journeyed to the ISS aboard the Crew Dragon spacecraft as part of NASA's SpaceX Crew-4 mission.

13 CAROLINE HERSCHEL

Herschel was a German-born astronomer who became the first woman to discover a comet in 1786. She was the sister of William Herschel, the astronomer who, on 13 March 1781, discovered the seventh planet from the Sun, Uranus. Herschel railed against the prejudice of the 18th century, the wishes of her mother and her training as a singer to join William in his study of the heavens, going on to discover eight comets in a period of 11 years. One of these is the periodic comet 35P/Herschel-Rigollet, which bears her name. She also discovered the dwarf galaxy companion of the spiral galaxy Andromeda, called Messier 110.

Additionally, without the aid of William, Caroline discovered three nebulae in 1783. Following her brother's death in 1822, she catalogued a further 2,500 of these celestial bodies. "At a time when women were excluded from science, Caroline Herschel managed to learn and contribute to astronomy, supported by her brother, William," García Peñaloza says. "Caroline, like many others after her, worked to serve a great purpose and was a pioneer in her time."

14 MARGARET BURBIDGE

Burbidge was one of the first scientists to realise that the elements which fill the cosmos are forged at the hearts of stars. This led to the realisation that stars couldn't forge elements heavier than iron at their hearts. She also campaigned against the discrimination she and other women faced in science, rejecting the Annie Jump Cannon Award in Astronomy in 1972, which was only presented to women.

"Burbidge's foundational work on the astronomical origins of the elements continues to be relevant," Dr Jillian Rastinejad, a NASA Einstein Fellow, says. "By setting out the conditions needed to create the heaviest elements, including gold and silver, her work led astronomers on a seven-decades-long hunt for a new type of cosmic explosion."

15 DEBRA FISCHER

Fischer is a professor of astronomy at Yale University and is a key figure in the detection and characterisation of exoplanets. Fischer was part of the team that discovered the first multi-planetary system other than our own Solar System in 1999. After this, Fischer went on to discover hundreds of planets outside the Solar System. This has included her leading a hunt for hot Jupiters around stars rich in elements heavier than hydrogen and helium, which astronomers call metals. In her lab, Fischer is developing the next generation of exoplanet-hunting instruments, which will search for Earth-like worlds with more precision than ever before.

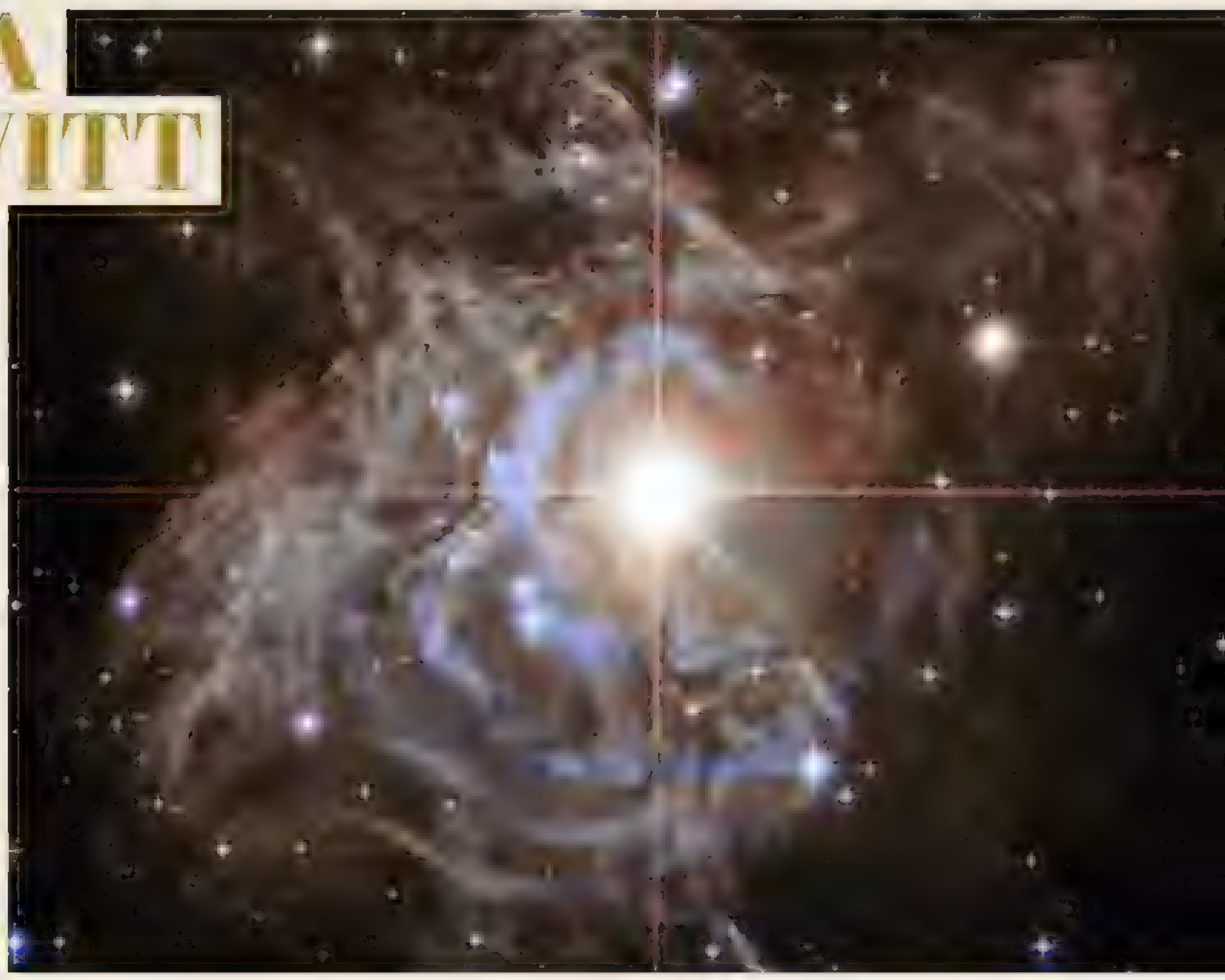
16 JILL TARTER

Tarter has become well known for her work in searching the cosmos for the telltale signs of extraterrestrial intelligence. Tarter, who has won a slew of awards and recognition for her science, currently serves on the management board for the Allen Telescope Array, which is an innovative array of 350 antennae at the Hat Creek Radio Observatory in California. This project surveys the universe for both expected and unexpected sources of radio waves and other astrophysical emissions. This should exponentially speed up the search for potential radio emissions emitted by technologies developed by distant extraterrestrial intelligence. If intelligent alien civilisations exist out in the cosmos and can be found, Tarter will likely be involved in uncovering them.

17 HENRIETTA SWAN LEAVITT

One of the most staggering things about space is the vast distances between ourselves and celestial objects. American astronomer Henrietta Swan Leavitt is responsible for determining how to measure distances to remote galaxies, showing the true scale of the cosmos. She did this while serving at Harvard College Observatory as a 'human computer', tasked with studying photographic plates to catalogue the positions and brightnesses of stars. This led to her discovery of the relationship between the brightness and period of stars called Cepheid variables, which transformed these pulsating stars into astronomy's first 'standard candles' for distance measurement.

Swan Leavitt's nomination for the 1925 Nobel Prize by Swedish mathematician Gösta Mittag-Leffler was halted when it was discovered that she had sadly died of cancer three years earlier.

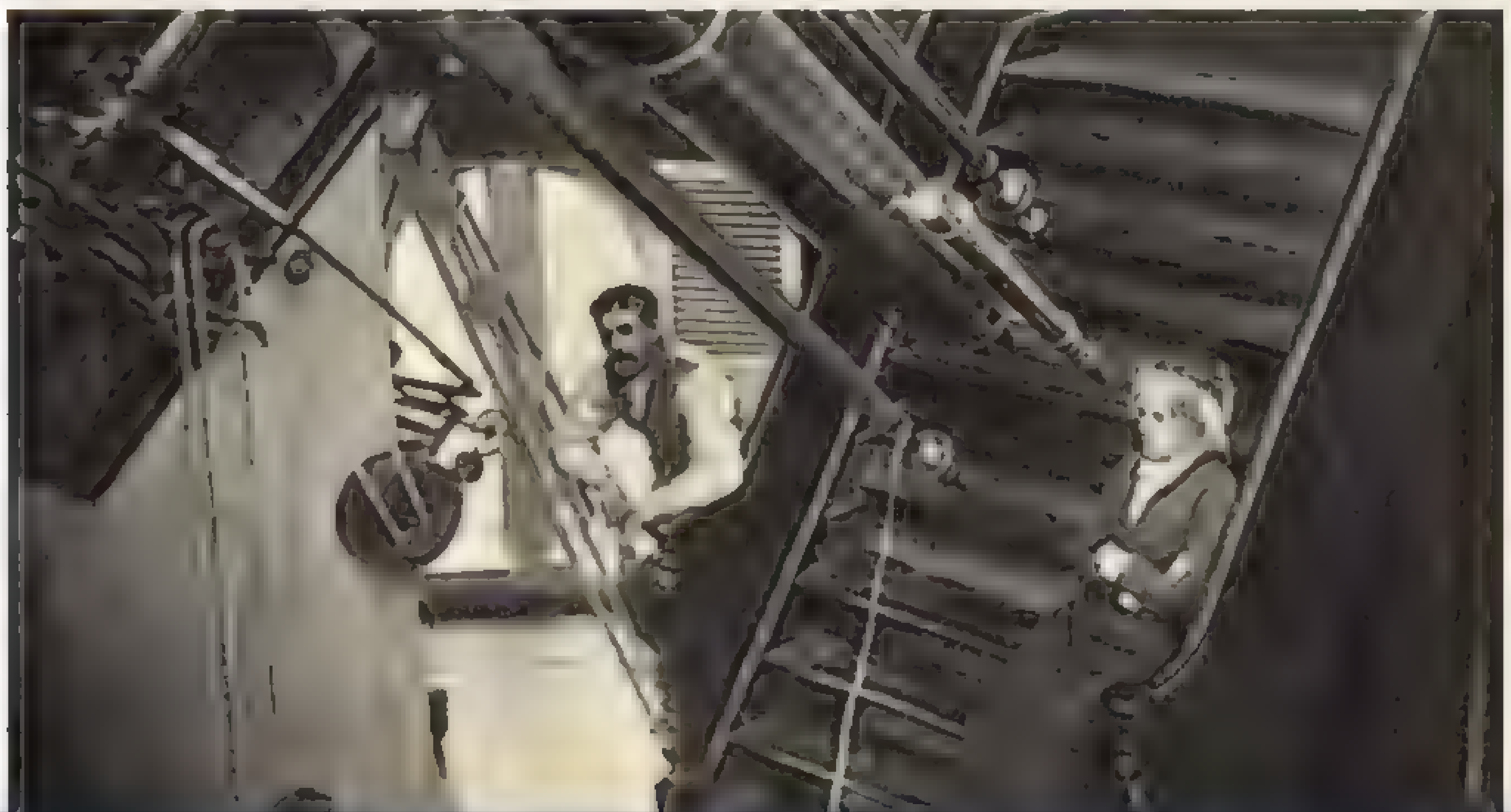


18 CHARLOTTE MOORE SITTERLY

One of the world's most honoured female astrophysicist, Moore Sitterly was renowned for her devotion to numerical accuracy in gathering data regarding the atoms of various elements and their characteristic energy levels. This led to the creation of reliable atomic tables that could be employed with confidence by other scientists for decades. Her work on solar spectroscopy at the Princeton University Observatory and the Mount Wilson Observatory also helped identify the chemical elements in the Sun.

19 MARIA MITCHELL

Mitchell is regarded as the first professional female astronomer in the United States. In October 1847 she discovered a comet that would be officially designated 1847 VI, but would later be nicknamed 'Miss Mitchell's Comet' in her honour. In 1865, Mitchell was appointed the first female professor of astronomy when she took a position at Vassar College. She was also the first woman elected to both the American Academy of Arts and Sciences and the American Association for the Advancement of Science. Mitchell was a passionate advocate of the advancement of women in higher education throughout her life.

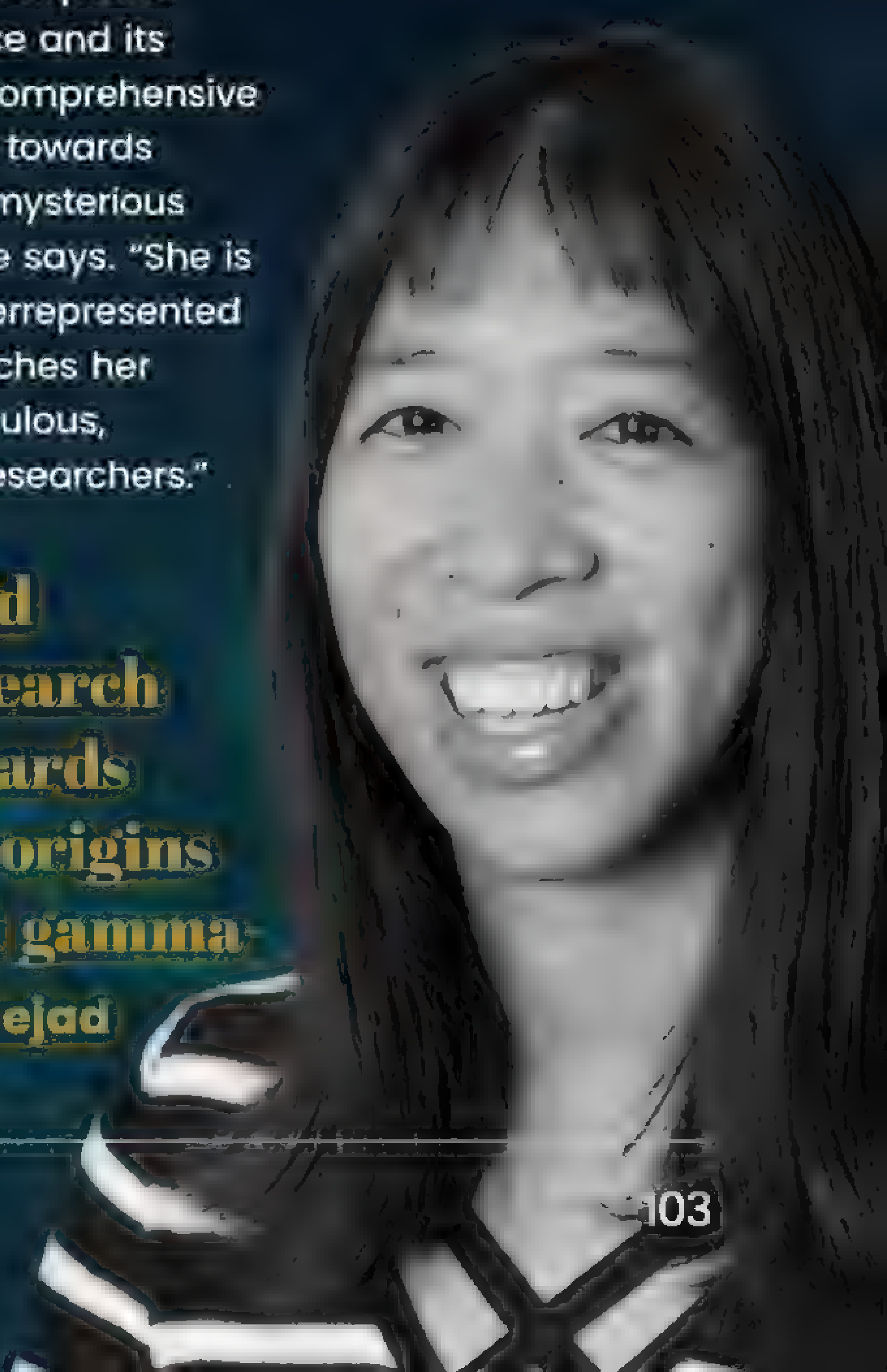


20 WEN-FAI FONG

Fong operates a research group at Northwestern University that studies astronomical transients, cosmic sources that change in brightness over time. The group has become a think tank for the next generation of female space scientists. "These transients encompass the most energetic explosions in our universe since the Big Bang itself. We use telescopes on the ground and in space operating across the electromagnetic spectrum to understand their mysterious origins," Fong told **All About Space** magazine. "Our work often requires waking up in the middle of the night and reacting to the discovery of a new transient. It is exciting and rewarding to have a 'conversation' with the universe in this way."

Fong explains that while her Northwestern group was never an attempt to create a hub for female scientists, its five female-identifying PhD students, which included Dr Rastinejad, got their place by merit, and the group welcomes all genders. "The first several PhD students in my group happen to identify as female," Fong continues. "Through this unique group, I have witnessed how they effectively build each other up in this competitive field so each reaches their fullest potential in ways I never thought possible in a research group." Rastinejad praises Fong, who was her PhD advisor, and explains her influence on space science and its future. "Wen-fai's novel and comprehensive research made vital progress towards understanding the origins of mysterious short gamma-ray bursts," she says. "She is a persistent advocate of underrepresented groups in astronomy and teaches her students to be creative, meticulous, collaborative and confident researchers."

"Wen-fai's novel and comprehensive research made progress towards understanding the origins of mysterious short gamma-ray bursts" Dr Rastinejad



INTERSTELLAR TRAVEL

AND HOW TO BECOME A SPACE TOURIST

Having explored much of the Solar System, attention is now turning to the stars beyond

As the spacecraft approaches the planet, things seem quite familiar. Sunlight glints off an expanse of blue ocean, and white clouds are corralled by gusts of wind. But a closer inspection is jarring – the continents are in the wrong places. That's because, for all its similarities, this isn't Earth. Instead, we're looking at the first historic images sent back of another world orbiting a star far beyond the Sun. In days gone by, such ideas were little more than a pipe dream. But the tide is turning.

In 2016, the late Stephen Hawking and billionaire Yuri Milner launched their Breakthrough Starshot project to an enthralled press conference. The goal was to one day fire lasers at sails strapped to tiny stamp-sized spacecraft, launching a swarm of explorers to Alpha Centauri – the nearest star system to Earth. Unfortunately the program has been put on hold indefinitely, but it has influenced other research.

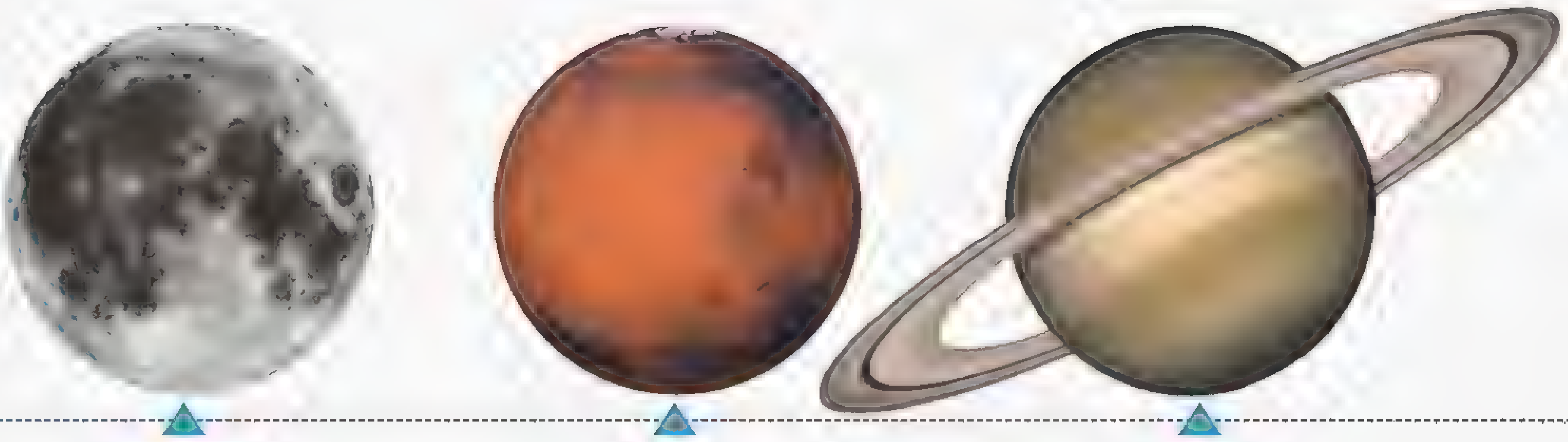
As things stand, we only have two distant emissaries of humankind that have departed the planetary system in which we reside: Voyager 1 and 2 – the probes sent to explore the outer planets in 1977. In 2012, measurements of the solar wind suggested Voyager 1 had left the magnetic influence of the Sun – one way of arguing it had departed the Solar System – with its twin reaching the edge in 2018. Yet they are nowhere near the next solar system. That's the problem with space – it really lives up to its name. A trip to the Alpha Centauri system requires us to travel a staggering 4.37 light years. At the speed of Voyager 1, it would take at least 30,000 years to get there.

That's why Hawking and Milner turned to an alternative solution. The goal was to take advantage of advances in technology miniaturisation. "We're already seeing one-tonne spacecraft being scaled down to a one-kilogram CubeSat," says Colin McInnes from the University of Glasgow. "You can imagine a similar device in the future weighing a gram."

If we can pack the payload of a modern space probe onto a chip the size of a thumbnail, then we'll have a lightweight explorer ready to be dispatched to the stars. However, it wouldn't be fired by traditional rocket-based propulsion – that's simply too slow. Instead, the Breakthrough

TRAVELLING NEAR THE SPEED OF LIGHT

How long does it take light to travel through the universe?



Target
Time it takes to get to the target from Earth

THE MOON — 1.28 seconds
MARS — 12.5 minutes
SATURN — 1.1 hours

Starshot team proposed firing pulses from a ground-based 100-gigawatt laser at sails strapped to a flotilla of micro-spacecraft. This should give each interplanetary spacecraft an almighty kick, accelerating them up to ten per cent of the speed of light. Send enough and a few survivors should make it to Alpha Centauri within a human lifetime. The onboard cameras could then send back those historic images of a distant alien solar system.

If it sounds simple, it isn't (and explains why the project has halted). "There are a number of engineering problems to solve," says Andrew Coates, a space scientist from University College London. Not least developing the 100-gigawatt laser required. There are safety concerns, too. "You'd have to worry about what a laser of that power would do to the atmosphere, or to aircraft or satellites orbiting above," says Coates. But McInnes believes there will come a time when technology converges and it will become feasible. "We could well see with interstellar travel that someone puts advancing technology together in a novel way to create something new," he says. Doing so would also bring us greater knowledge of the environment between the stars – the interstellar medium – and kick-start a revolution in our understanding of this under-explored region of space.

Yet for many, the real dream of interstellar travel is not to dispatch tiny robots, but instead to send people to explore these far-off solar systems, just as early terrestrial explorers sailed vast oceans to conquer new continents. "There is no doubt that humans are more efficient explorers than robots," says Ian Crawford, a planetary scientist from Birkbeck, University of London. Yet we are about as far from travelling between the stars as you can get. We've barely dipped our toes into the vast cosmic waters, and instead we remain largely in low-Earth orbit, with only a dozen American men having left their footprints in the lunar dust.

As we've seen, the distances involved in interstellar travel are more than intimidating. If we are to cover them within a human lifetime, then we need to be able to accelerate people to at least ten per cent of the speed of light – something that brings with it a whole host of new challenges. "The real limiting factor is mass," says Crawford. The trouble with human missions is that we need food, water and oxygen to survive. Providing all of these things significantly ramps up the mass of the mission. To accelerate that mass you need fuel, which itself adds mass, requiring even more fuel. It's a vicious cycle. "It becomes such a difficult problem that it would be irresponsible to argue that it is at all realistic," Crawford says.

But that's because in that scenario we're restricting ourselves to achieving the goal of a crewed interstellar mission in a single human lifetime. We could instead invoke a plan that is dear to science-fiction writers:

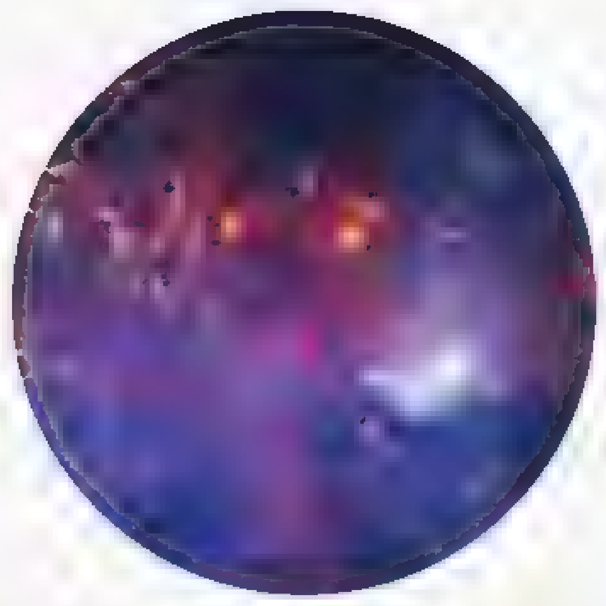
A Physicist Stephen Hawking threw his name behind the Breakthrough Starshot mission to Alpha Centauri

HOW INTERSTELLAR TRAVEL AFFECTS THE BODY

- Changes in gravity can affect bone mass
- Radiation from cosmic rays can cause radiation sickness
- Radiation can also cause cataracts
- Long-term isolation can cause psychological trauma

PLUTO
4.6 hours

PROXIMA CENTAURI
4.2 years



CENTRE OF THE MILKY WAY
30,000 years

EDGE OF OBSERVABLE UNIVERSE
46.5 billion years

THE SPACESUIT

A key part of any space traveller's equipment

1 Oxygen supply

While the environment aboard your craft would have its own oxygen, if you needed to venture outside of your spaceship then breathable air is a must.

2 Visor

While most of the journey would be far from any bright light, a visor is important for when you are up close to a star. Without one, the searing light could easily blind you.

3 Communications

When you're encased in a spacesuit, having radio communication with your fellow astronauts is key – especially as you're too far from Earth for quick help.

4 Water supply

Water is a vital ingredient for life. You'll certainly need it if you're roving out and about once you reach your final destination.

THE SPACECRAFT

Scientists and science-fiction writers alike have long dreamed up ways of travelling between the stars

Daedalus

In the 1970s, the British Interplanetary Society conducted research into a rocket that could travel between the stars. Their aim was to send their fusion-powered spaceship to reach Barnard's Star in 50 years.

Project Orion

This would have used controlled nuclear explosions to propel a craft. The difficulty is that many countries are signed up to an international treaty banning the detonation of nuclear devices in space.

Breakthrough Starshot

This idea from Hawking and Milner was to send a swarm of tiny probes to the Alpha Centauri system by firing a powerful laser at sails strapped to the miniature machines.

Sanger photon rocket

Eugen Sanger suggested using antimatter as the propulsion mechanism for a spacecraft in the 1950s, as when antimatter collides with matter it creates energy that could propel the craft forwards.

Bussard ramjet

One of the problems with interstellar travel is the need to carry fuel. To get around this, a ramjet could use magnetic fields to scoop up interstellar material as it goes, which could then be used as fuel.

INTERSTELLAR ROAD MAP

Given how difficult it is to travel far from Earth, where might our interstellar travels take us?

THE LOCATIONS

Alpha Centauri
Distance from Earth: 4.3 light years
Current travel time: 30,000 years
Interstellar speed travel time: 43 years
This three-star system includes Proxima Centauri, which is the nearest star to Earth after the Sun. It's confirmed there are at least three planets around this star.

Barnard's Star
Distance from Earth: 5.96 light years
Current travel time: 42,500 years
Interstellar speed travel time: 60 years
One of the fastest moving stars in the galaxy, this is also the closest star to Earth, after the Sun, that is visible from the Northern Hemisphere.

Wolf 359
Distance from Earth: 7.8 light years
Current travel time: 55,500 years
Interstellar speed travel time: 78 years
This red dwarf is located in the constellation of Leo and can only be seen through a large telescope.

Sirius
Distance from Earth: 8.6 light years
Current travel time: 61,250 years
Interstellar speed travel time: 86 years
Sirius is the brightest star in the night sky as it is one of the closest to us. It is part of a double star system.

Gliese 65
Distance from Earth: 8.7 light years
Current travel time: 62,350 years
Interstellar speed travel time: 87 years
This star, seen in the constellation of Cetus, is actually a binary system of two stars encircling each other every 26.5 years or so.

Ross 154
Distance from Earth: 9.7 light years
Current travel time: 69,100 years
Interstellar speed travel time: 97 years
This star, found in the constellation of Sagittarius, can only be seen with apertures of three inches or larger.

Ross 248
Distance from Earth: 10.3 light years
Current travel time: 73,750 years
Interstellar speed travel time: 103 years
This small star in the constellation of Andromeda emits just 0.2 per cent of the Sun's light.

Epsilon Eridani
Distance from Earth: 10.5 light years
Current travel time: 75,000 years
Interstellar speed travel time: 105 years
This bright star, visible with the naked eye, has a confirmed planet orbiting around it and has been a popular interstellar travel target in science fiction.

Lacaille 9352
Distance from Earth: 10.7 light years
Current travel time: 76,700 years
Interstellar speed travel time: 107 years
Visible in the Southern Hemisphere with binoculars, this star is smaller and cooler than our Sun.

Ross 128
Distance from Earth: 11 light years
Current travel time: 78,000 years
Interstellar speed travel time: 110 years
Ross 128 is a red dwarf star whose orbit around the Milky Way will bring it closer to us in the future.

the generation ship. Instead of going fast, we could go slow, meaning that much less energy is required to accelerate the craft. The consequence is that the mission would take far longer than a single human life span. "You'd have some large, self-containing colony in which generations live out their lives and it is their descendants who reach the destination," Crawford says.

However, in order to maintain sufficient genetic diversity on board to prevent too much inbreeding, studies have suggested you'd need an initial crew of between 75 and 150 people. Providing living quarters and supplies for the equivalent of a small hamlet for hundreds of years would require your ship to be enormous – kilometres long in Crawford's estimation.

"You face engineering challenges either way," he says. Either you have to build a small ship but struggle to get it up to the lofty speeds required for quick passage, or you have to struggle to build an enormous ship here in the Solar System that will carry hundreds of people for hundreds of years. The latter case is also particularly prone to ethical concerns. You'd be creating generations of humans 'imprisoned' on a craft with no memory of home and no hope of seeing the eventual destination.

Of course, this is all based on the assumption that a human life span is somewhere close to 100 years. What if that figure is only a product of the times we live in? After all, we're living twice as long on average than we did many centuries ago. Perhaps there is no upper limit to how long we can live. That's the view of gerontologist Aubrey de Grey, who sees ageing as a disease that's curable like any other. He believes that the first person to live to 1,000 is alive today. A remarkable claim, but less so when you realise that he isn't talking about one miraculous boost in medical understanding to extend your life that far. Instead, one initial breakthrough could extend your life sufficiently so that you're always ahead of the medical curve, living ten years longer until another breakthrough occurs that will extend your life further. Then again, maybe he's wrong.

Given all these significant hurdles, it's no surprise that global space agencies, including the European Space Agency (ESA), are seriously looking into another alternative: human hibernation. The ESA's Topical Team on the subject is tasked with determining a probability based on current knowledge of controlled use of human hibernation being applicable to human spaceflight in a foreseeable future, along with rough estimates on the timeline, potential showstoppers and gains. If we could master such methods, the advantages are clear.

You'd need a much smaller crew, and reproduction on board would no longer be necessary. It's also better psychologically for those on board as they don't have to experience the rigours of the voyage. Plus, as they are inactive, they won't use as many resources, meaning the mass of the mission could be kept to a minimum. "It is very early days and no one knows if it is possible or not," says Crawford, "but it's not impossible to imagine that in 100 years, human hibernation may be possible, making it easier to send humans to the stars."

If we do make it to the stars, it would make 'astronaut', which means 'star-sailor', a more accurate term for our space travellers. The challenges are great, but like all successful endeavours in human history, you can't achieve something unless you set yourself a goal. It is almost certain that robots will go before us, as in the early days of space exploration. But one day, it might be possible that your descendants will gaze upon the continents, clouds and oceans of a familiar yet far-off world and be the first to set up a human outpost among the stars.

We already fire laser beams at the Moon, but for star sailing they would have to be a lot more powerful

Colin Stuart
Astronomer and space science writer
Astronomer and space science writer
Colin holds a degree in astrophysics, has written over 17 books on space and even has an asteroid named in his honour 15347 Colinstuart

REQUIREMENTS FOR INTERSTELLAR TRAVEL

20:20 vision or the ability to correct to it

Good eyesight is crucial for the wide range of intricate activities required for an interstellar astronaut.

Fit and healthy, with a blood pressure of 140/90

Far from home without the ability to return to Earth quickly for medical attention, overall health is key.

Psychologically strong

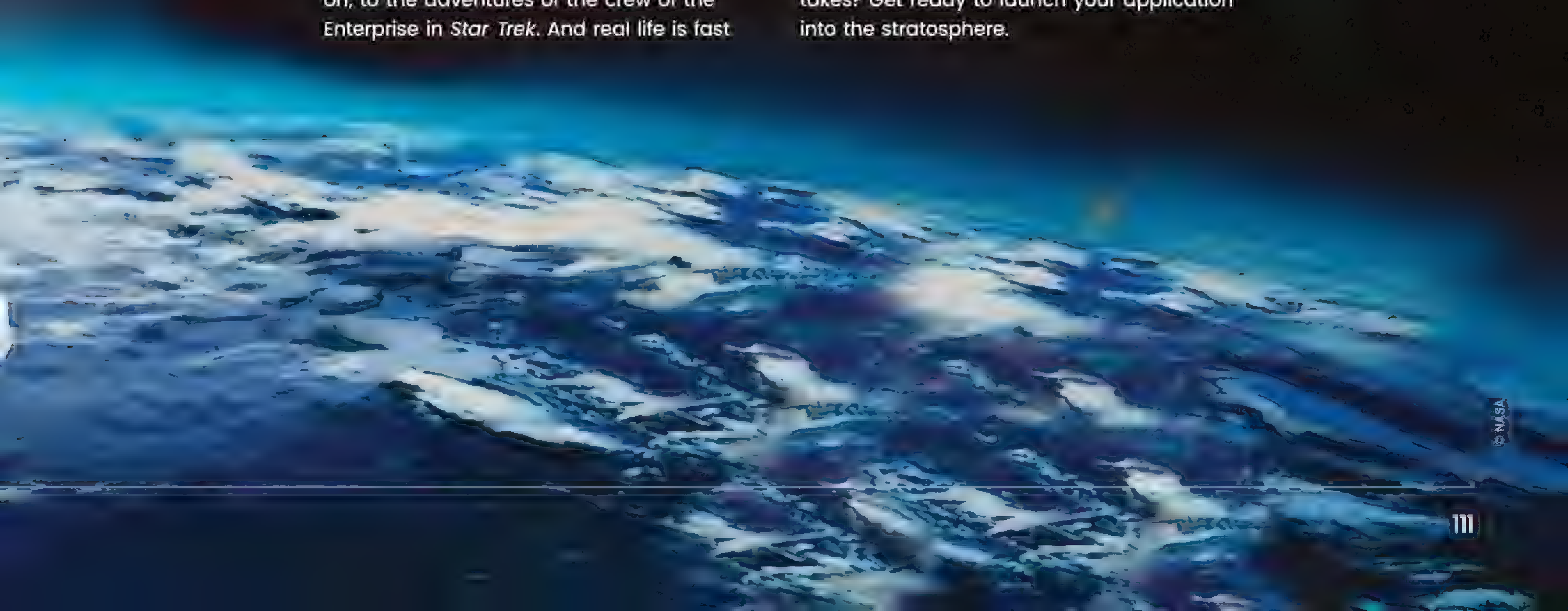
Being isolated and cut off from your home planet with no easy way back is difficult – the right mental stuff is a must. Remaining calm under pressure is also vital.

DO YOU HA
IT TAKES
ASTRO

AVE WHAT TO BE AN NAUT?

NASA intends to reach Mars in the next decade, and science-fiction movies and TV shows are making space exploration look more exciting than ever. But have you ever asked yourself if you're really cut out for life as an astronaut? In 2024, NASA received over 8,000 applications from budding astronauts, and it's no surprise that becoming an astronaut is appealing. Science-fiction movies make life in space look star-shatteringly exciting, from *The Martian*, which NASA experts consulted on, to the adventures of the crew of the Enterprise in *Star Trek*. And real life is fast catching up. NASA's journey to Mars is well underway, with a plan that will see astronauts reaching Mars orbit some time in the 2030s.

Increasingly, space agencies aren't the only workplaces available to aspiring space travellers. Private companies like SpaceX and Blue Origin will soon offer budding astronauts the chance to work – and even take a holiday – among the stars. But becoming an astronaut is difficult and time-consuming, and very few people are up to the job. Think you might have what it takes? Get ready to launch your application into the stratosphere.



© NASA

WHAT DO YOU NEED TO APPLY?

Before beginning the training to prepare you for space, there are a set of entry requirements you have to meet. These differ depending on which space agency you want to work for, whether that's NASA in the United States or the European Space Agency (ESA) in the UK and Europe. Both the ESA and NASA require a degree in engineering, science or mathematics, as well as 1,000 hours of pilot-in-command time in an aircraft or three years (two years for NASA) of related experience.

You also need to be physically up to the job. NASA puts would-be astronauts through a long-duration astronaut physical that includes fitness and eye tests. Space agencies are looking for recruits who are fit and healthy so they can cope with the demands of space and are less likely to become ill when they're so far away from Earth.

Speaking with Kevin Fong, a consultant at University College Hospital in London specialising in anaesthesia and pre-hospital care, reveals important medical questions about space travel and ensuring the flight-readiness of crews: "There are a lot of physical requirements, but personality is just as important, such as people working together as part of a team. We're also looking for evidence of where decisions have consequences."

Personality, physical fitness, experience and education are all required, but the final decision of who makes it to the team can depend on what the agency is looking for during any given recruitment push. "Space agencies often select astronauts depending on what the mission requires. Long-duration missions will need a broader skill set than, say, the test pilots who crewed the Apollo missions, for example," explains Fong.

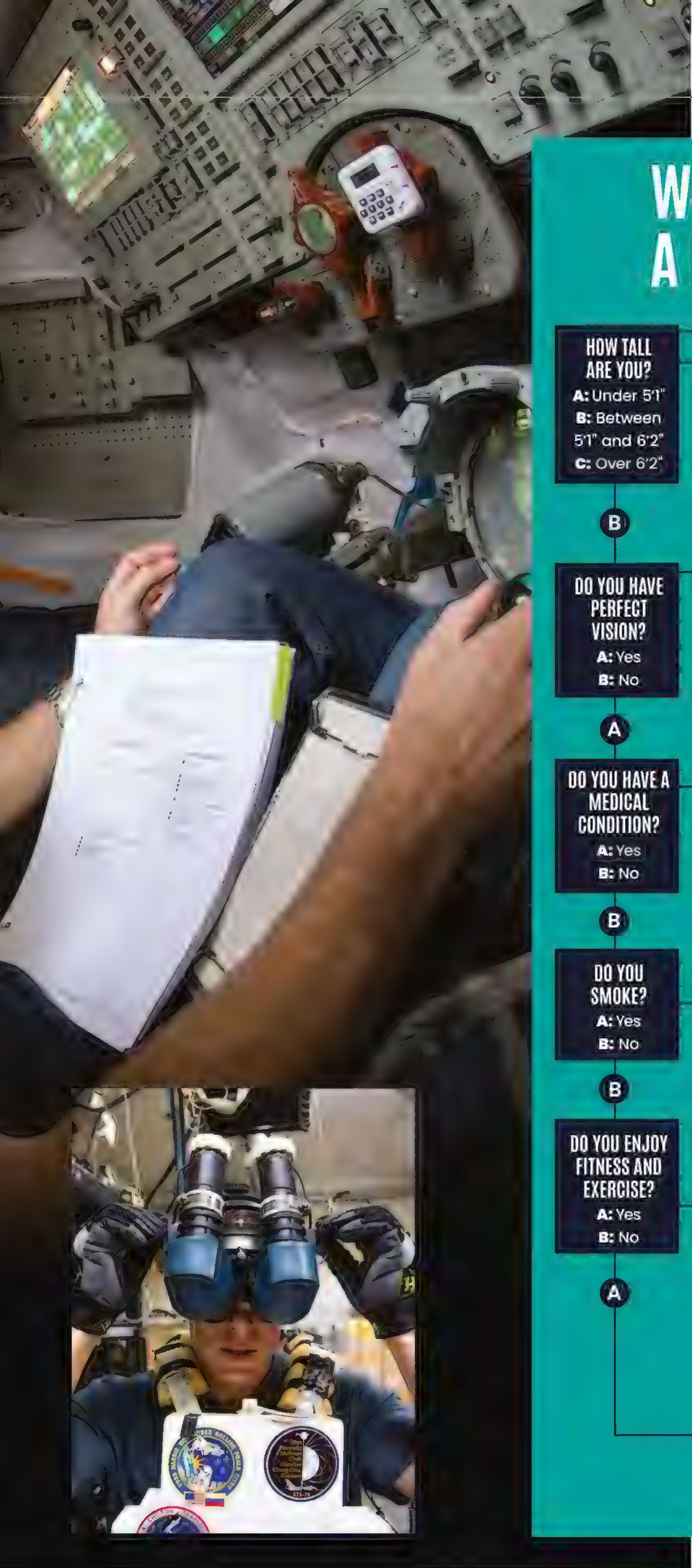
"There are a lot of physical requirements, but personality is just as important"

Kevin Fong

ESA astronaut Thomas Pesquet taking part in training on the Soyuz docking simulator

Robert L. Curbeam of NASA seen wearing a training variant of the Extravehicular Mobility Unit spacesuit

NASA astronaut Michael S. Hopkins using a virtual-reality headset in the Space Vehicle Mockup Facility



WOULD YOU PASS A HEALTH CHECK?

HOW TALL ARE YOU?
A: Under 5'1"
B: Between 5'1" and 6'2"
C: Over 6'2"

A / C → **YOU'RE NOT LIKELY TO BECOME AN ASTRONAUT**
Every space agency has a slightly different set of astronaut height requirements. That means if you didn't make the cut this time you might still be in with a chance, especially as mission demands shift over the next few years. You're in with the best chance if you measure up between 5'1" and 6'2".

B ↓

DO YOU HAVE PERFECT VISION?
A: Yes
B: No

B → **YOU'RE NOT LIKELY TO BECOME AN ASTRONAUT**
Most space agencies are looking for candidates with 20/20 vision. As the ESA points out on its website, most disqualifications during the recruitment process are due to problems with candidates' eyesight – and that's hardly surprising.

A ↓

DO YOU HAVE A MEDICAL CONDITION?
A: Yes
B: No

A → **YOU'RE NOT LIKELY TO BECOME AN ASTRONAUT**
Each medical condition is different and often assessed on a case-by-case basis, but if you have a disease, psychiatric condition or a disability it may stop you from becoming an astronaut. Although being in space isn't necessarily dangerous, you need to be as fit and healthy as possible.

B ↓

DO YOU SMOKE?
A: Yes
B: No

A → **YOU'RE NOT LIKELY TO BECOME AN ASTRONAUT**
You wouldn't be able to drink, smoke or take drugs on the job or deal with the emotional and physical symptoms of withdrawal. Of course, if you're willing to work on beating your addiction before you apply there's a chance you'll be considered, but that would require assessment.

B ↓

DO YOU ENJOY FITNESS AND EXERCISE?
A: Yes
B: No

B → **YOU'RE NOT LIKELY TO BECOME AN ASTRONAUT**
Being an astronaut is very physically demanding, from training to carrying out missions in space, through to the physiological effects of weightlessness. This means if you don't enjoy working out you could still become an astronaut, but you're going to have to do more cardio.

A → **YOU COULD BE AN ASTRONAUT**
You've passed the first set of health tests, which means there's a chance you could become an astronaut one day. You enjoy exercise, your vision is laser sharp, you're the right height and there aren't any medical conditions that could cause problems for you or future missions when you're in space.

TIME TO BEGIN TRAINING

After making it through the initial entry requirements, candidates are invited to take part in a screening process. In 2008, when British astronaut Tim Peake began this process, the ESA took roughly 900 candidates through a series of tests before whittling them down to just ten over the course of a year. But making it through the application process, the screening process and the excitement of being one of the lucky chosen few is only the beginning. You can only become a full-fledged astronaut if you successfully complete the next two years of training.

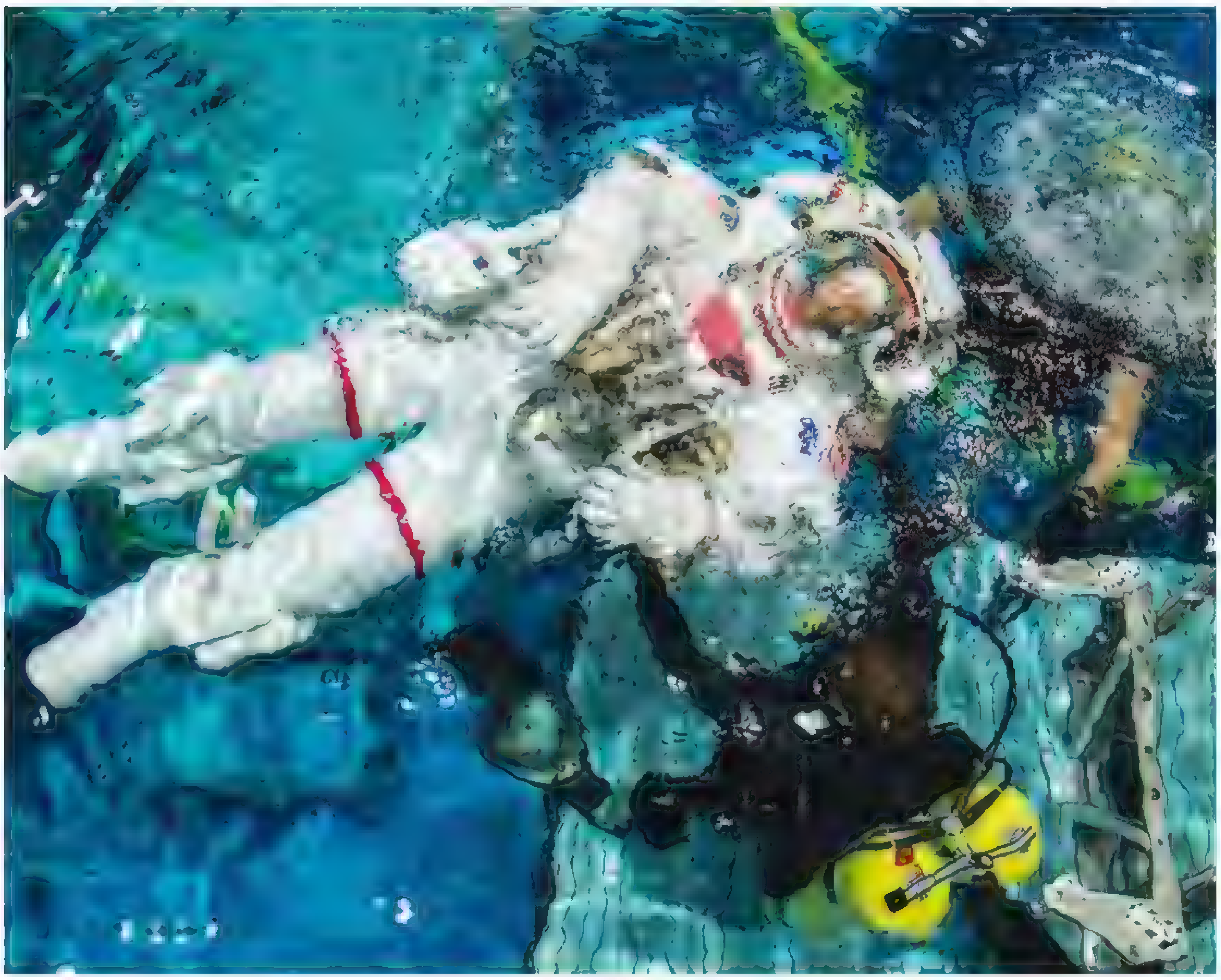
This involves different activities depending on which space agency you're working for, but it generally includes military water survival training to replicate zero gravity; emergency medical training; scuba diving; swimming tests; and exposure to different kinds of atmospheric pressure. Retired NASA astronaut Dorothy Metcalf-Lindenburger says: "In one training scenario we were in a swimming pool, turned over underwater in a mock spacecraft and had to get out of any door or window. The second time the door or window they assigned and the third time you had to do it blindfolded. That was my least favourite day on the job."

A lot of the training involves activities you wouldn't necessarily experience in space, but which utilise a lot of the same skills. In a NASA podcast about astronaut training, astronaut Randy Bresnik spoke about his caving adventures. "You start out, just like on any training, with basic caving stuff, and rappelling and climbing. Then you went into a day where you're in really narrow caves and it's really winding about, getting lost, navigation and being able to go through squeezes and navigating through tiny areas of the cave to be able to overcome any claustrophobia," Bresnik recalls. "It was really applicable to what we do in space," he explains, "because in space you don't know what time it is, because every 45 minutes you get a sunrise, and then a sunset, and that happens 16 times a day."

There's also a considerable amount of time spent in the classroom learning about space and also languages, so you can talk with other astronauts on board the International Space Station (ISS), many of which have come from the Roscosmos Russian agency.

The ESA's Paolo Nespoli participating in spacewalk training in the Partial Gravity Simulator (POGO)

ESA astronaut Thomas Pesquet undergoing underwater spacewalk training at NASA's Johnson Space Center



Once training is complete, qualified astronauts are still unlikely to go into orbit for years. They complete simulated spacewalks, train with international partners and learn more to prepare them for their designated role. As retired Air Force pilot (and former NASA astronaut) Colonel Gregory Johnson explained in an interview on the NASA YouTube channel: "Once you become an astronaut, you specialise in your particular area. In my case it was operating the Space Shuttle, learning to land, rendezvous two different objects and learning to operate the robotic arms on the ISS and the Space Shuttle."

> "Once you become an astronaut, you specialise in your particular area. In my case it was operating the Space Shuttle, learning to land and rendezvous two different objects"
>
> **Gregory Johnson**

Even after you're selected for a flight, the mission training may take another couple of years, which will involve further simulations, classroom training and way more learning so that you are fully prepared for your future mission. It may take time, but this ensures that astronauts are fully prepared for spaceflight.

Bresnik explains about the training involved to prepare astronauts for life on board the ISS. "There's a lot of station training because you've got to be able to do everything. You've got to be able to execute the payloads and experiments. At the same time, you've got to be able to do Earth observation."

The ESA's candidates from 2010 experiencing weightlessness in between their training sessions

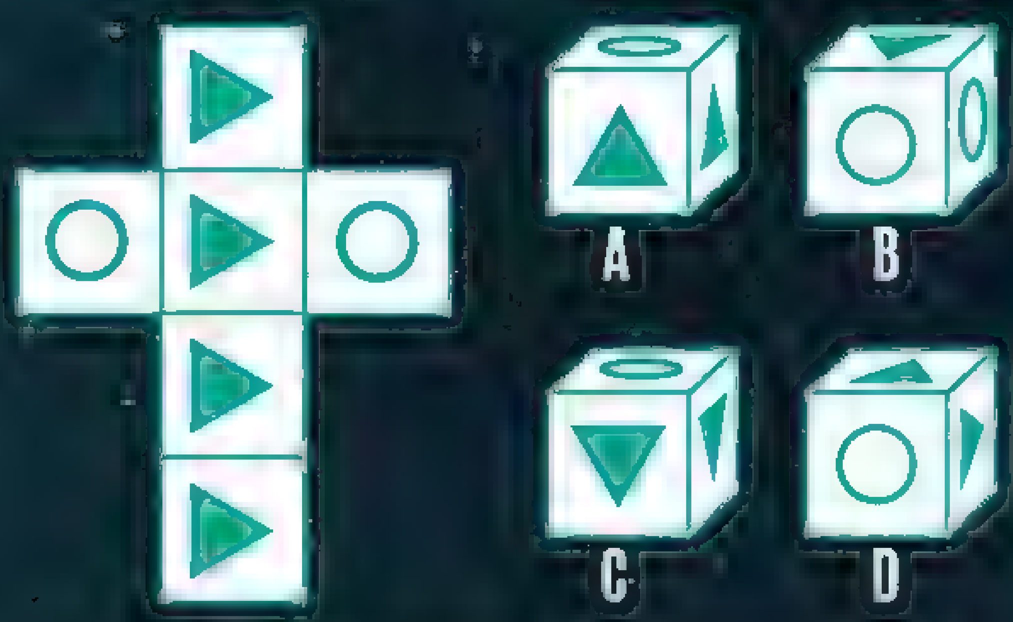
ESA astronaut Matthias Maurer taking part in sea survival, which is a staple of training

© ESA

TEST YOUR SPATIAL AWARENESS

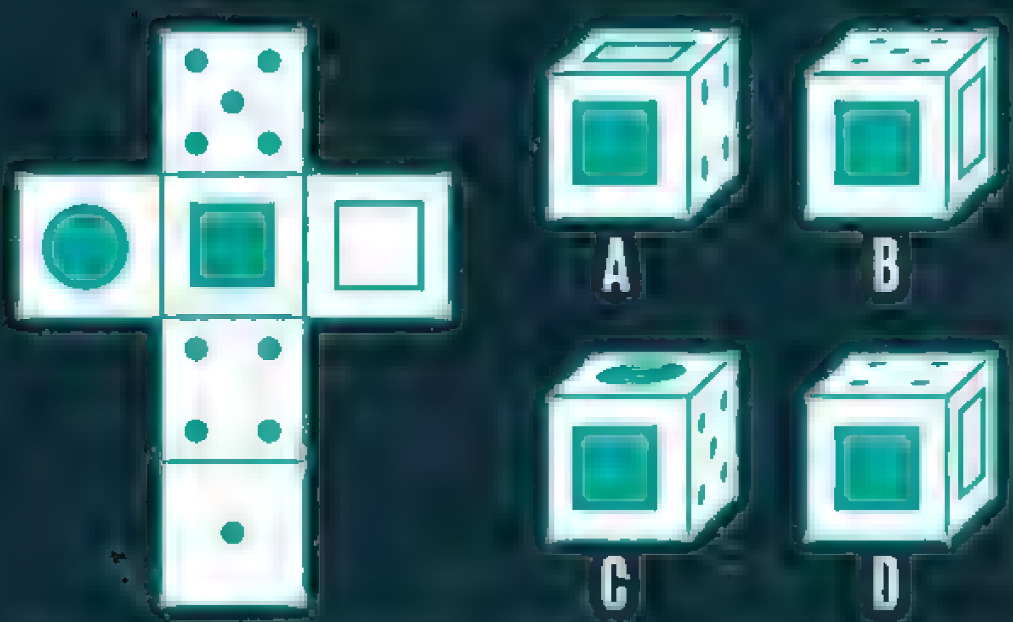
SCENARIO ONE

Which cube cannot be made from the unfolded cube?



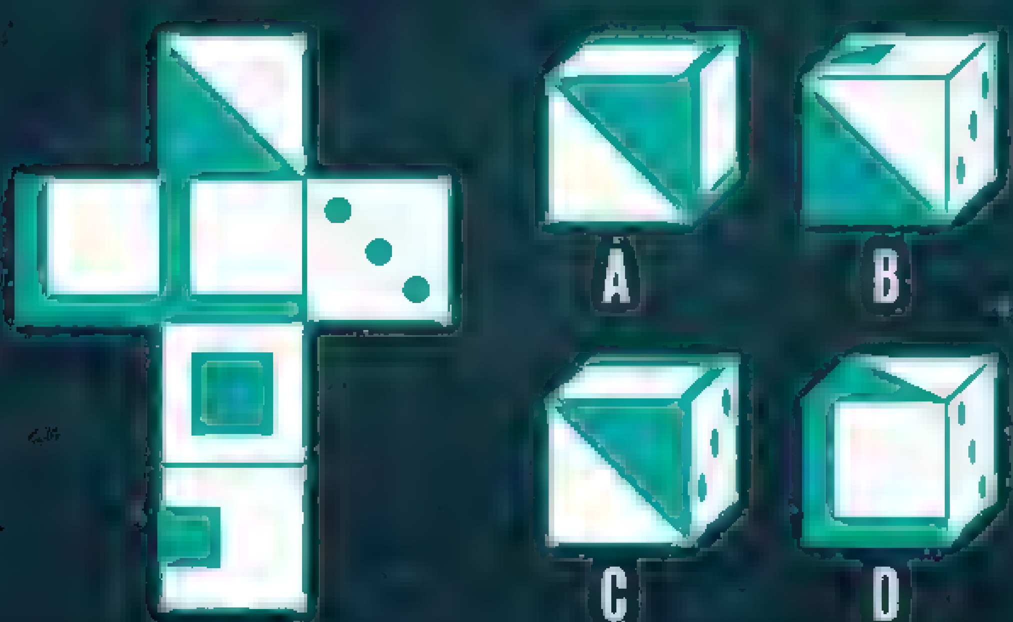
SCENARIO TWO

Which cube cannot be made from the unfolded cube?



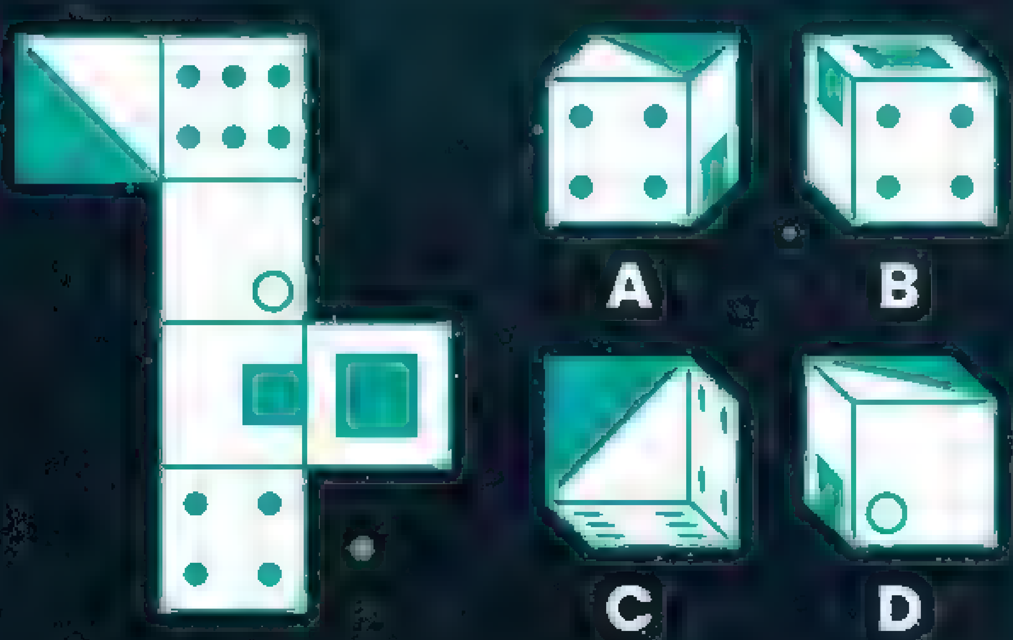
SCENARIO THREE

Which cube cannot be made from the unfolded cube?



SCENARIO FOUR

Which cube cannot be made from the unfolded cube?



Answers: 1. B / 2. D / 3. C / 4. D

HOW WOULD YOU RESPOND IN THE FOLLOWING SITUATIONS?

YOU'RE GOING ABOUT YOUR DAILY TASKS AND YOU SEE A SMALL FIRE HAS STARTED ABOARD THE SPACECRAFT...

WHAT DO YOU DO?

A: Fight the fire with an extinguisher
B: Call mission control on the ground
C: Raise an alarm and let everyone else know
D: Leave the area straight away

PHEW, THE FIRE IS OUT.
ALL THE CREW MEMBERS ARE SAFE AND THE AREA LOOKS SAFE...

WHAT SHOULD YOUR NEXT STEP BE?

A: Figure out a way to leave the spacecraft
B: Investigate the source
C: Stay far away from the affected area
D: Call mission control on the ground

A SOLAR FLARE HAS DIRECTED DANGEROUS LEVELS OF RADIATION TOWARD YOUR SPACECRAFT...

WHAT DO YOU TELL THE REST OF THE CREW TO DO?

A: Evacuate the spacecraft
B: Put on a radiation-absorbing suit
C: Go to a special area within the spacecraft that absorbs radiation
D: Keep working because a bit of radiation never hurt anyone

DEBRIS HAS HIT THE HULL OF THE ISS, WHICH CREATES A HOLE AND MAY CAUSE DEPRESSURISATION...

WHAT DO YOU DO?

A: Tell the crew to get into their spacecraft and close the hatches
B: Try and plug the hole quickly
C: Contact mission control
D: Put on an oxygen mask

ANSWERS

The first step in emergency training is often to warn others, followed by leaving the affected area and starving the fire of oxygen.

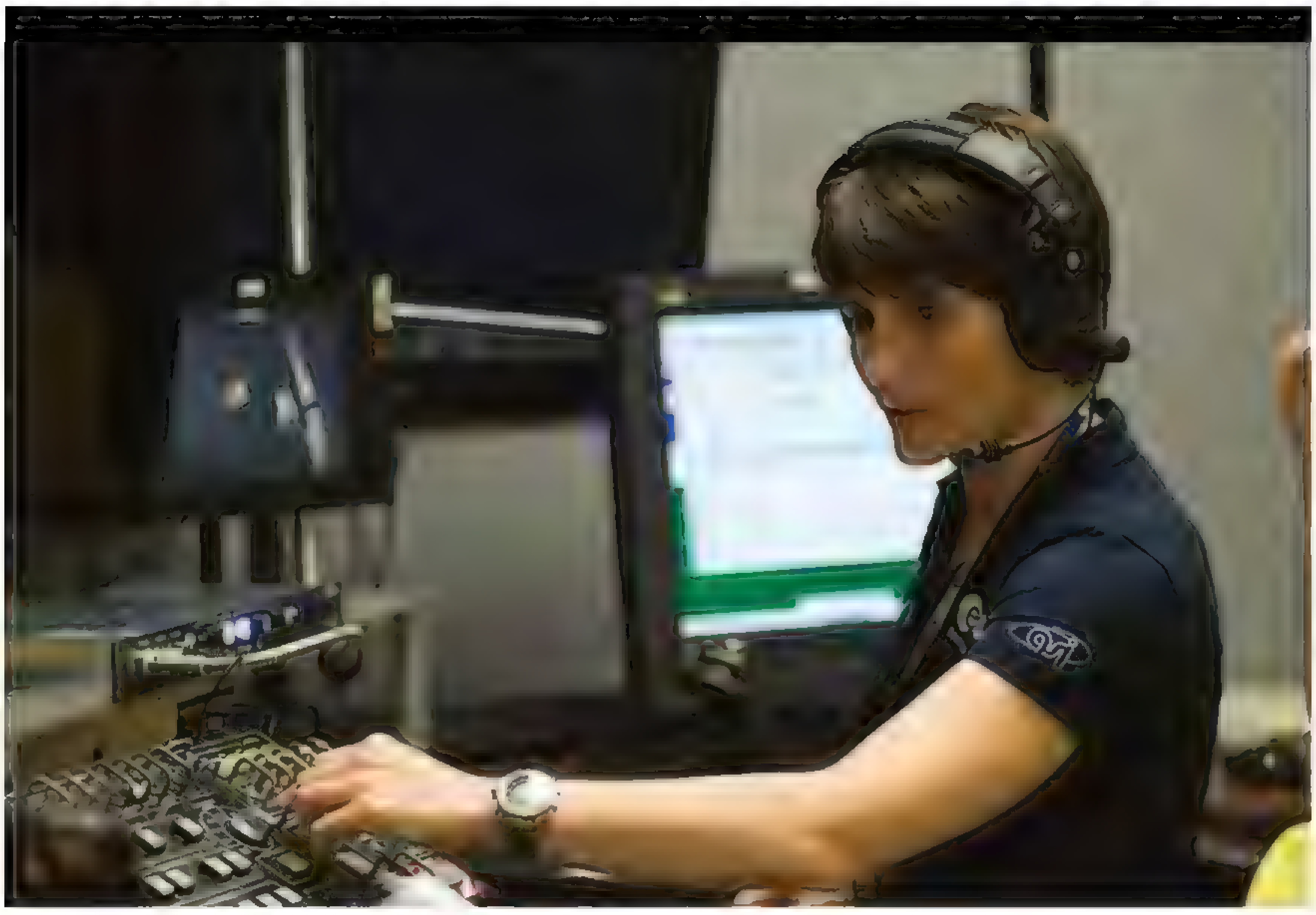
The next step is to gather information. You need to work with crew members and mission control to find out what happened.

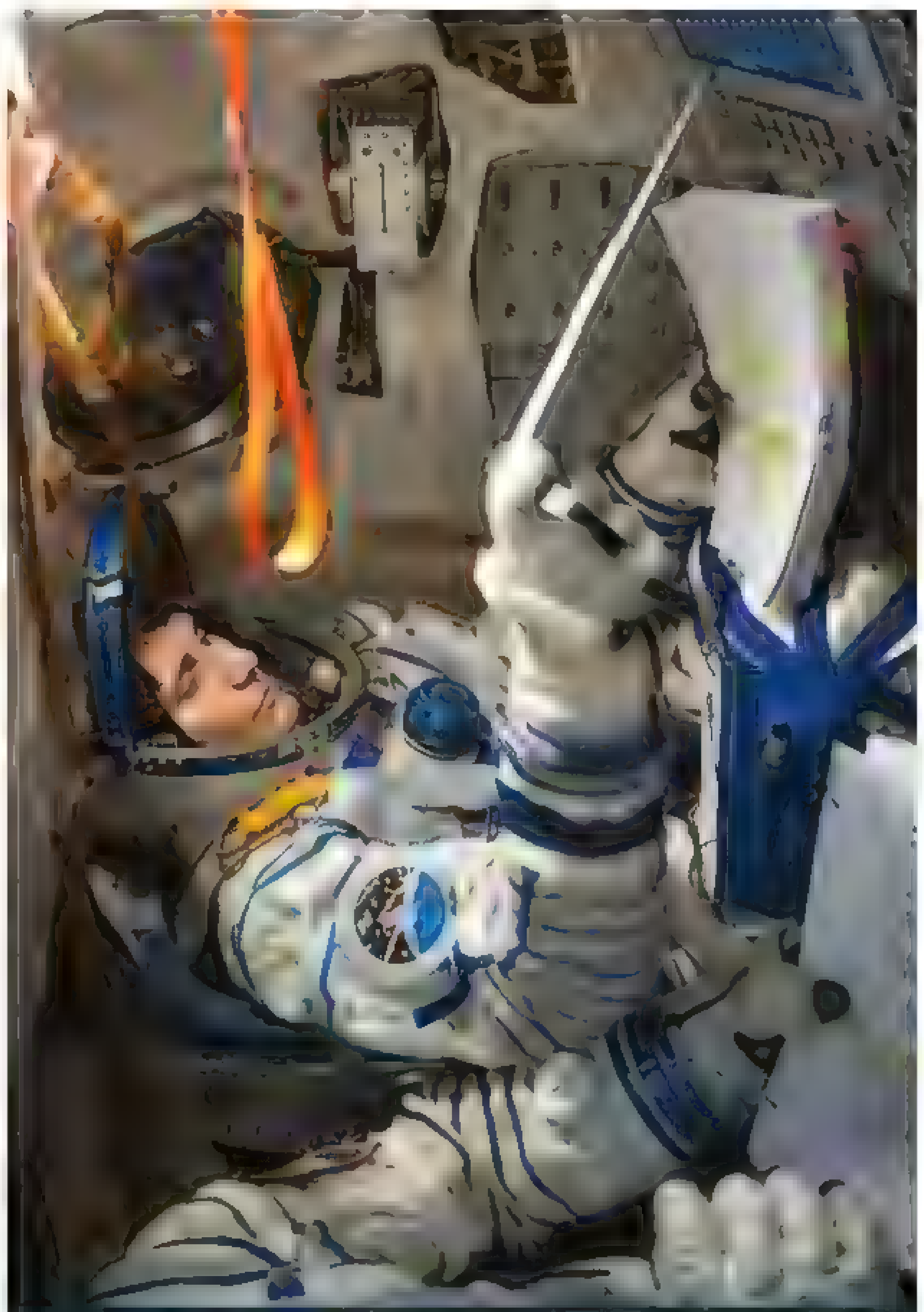
There are special areas of the ISS that astronauts can go to that help stop radiation from attacking the body.

You should return to your spacecraft, which acts as a lifeboat and close hatches to minimise damage in case the hole is big.

SKILLS YOU CAN TAKE WITH YOU

If you don't make it through the application process or training, it doesn't necessarily mean that it is all over. As Mike Mongo, astronaut teacher and author of *The Astronaut Instruction Manual*, says: "The modern space industry is also made up of private space companies, all of which are being built on business models that will require more astronauts". These companies are likely to require similar kinds of candidates, but as Mongo points out, they may need a more diverse bunch of people. "Pretty much every line of work we do on Earth will soon have parallel positions in space," Mongo says. "All types of personality traits, physical characteristics and cultural backgrounds are in demand for becoming an astronaut. Diversity of talents, as well as diversity of people, will be the next big determinant of astronaut selection."





DO YOU HAVE THE RIGHT STUFF?

The application process favours the best of the best, the training is exciting but extremely demanding and the competition is as fierce as it gets. But with the right experience, mindset and a love for physical challenges, you could become the next Tim Peake or Peggy Whitson.

© ESA; NASA

ALL CHANGE?

A recent study released by the University of Ottawa questions whether dark matter and dark energy even exist. The research puts forward the idea that dark matter and dark energy are actually illusions caused by the fading of the universe's forces over time. It will be very interesting to see if this research challenges the established concepts in astronomy.

MYSTERIES OF THE UNIVERSE

CAN AI SOLVE THE MYSTERY OF DARK ENERGY?

Scientists are keen to understand more about dark energy, and they're drafting in artificial intelligence to aid them

Reported by David Crookes

Scientists cannot definitively explain the exact nature of dark energy. It's believed to have a significant effect, accelerating the expansion of the cosmos, but despite making up about 70 per cent of all of the mass and energy in the universe, it remains a mystery that researchers have longed to get to the bottom of. By amassing and analysing an abundance of data, astronomers have been getting closer and closer to a better understanding. One of the big breakthroughs in recent times has been the Dark Energy Survey, which was published in 2021. Based on observations made between 2013 and 2019, this huge dark matter map has provided a solid amount of data for researchers and is proving capable of throwing up many interesting results.

One of the problems with analysing data such as this is that there's a lot of it. Another issue when seeking a conclusion to a study is that there still isn't enough. But help is at hand to resolve both of those niggles thanks to the advances of artificial intelligence (AI). By getting computers to take a look at the data, the idea is that AI will be able to make speedy assessments with unmatched precision. And that is exactly what's happened, according to scientists at University College London.

A team of academics led by Niall Jeffrey and involving the Dark Energy Survey collaboration has made use of the Dark Energy Survey's matter map. Taking data from the first three years of observation, the team have been able to plot the whereabouts of dark matter across a quarter of the sky in the Southern Hemisphere. They've done so using a method called gravitational lensing. Since dark matter doesn't interact with light, it has entailed observing the distortion of light from distant stars on its way to Earth, and that has given them a dataset of 100 million galaxies showing dark and visible matter.

Rather than manually inferring the influence and properties of dark matter from this map, the team employed AI to generate simulations of different universes based on the data, each drawing upon a different mathematical model of the universe. They did so using the DiRAC high-performance supercomputers at Cambridge and Edinburgh universities, allowing for much faster results due to the immense power of the machines. "We generated 800 independent simulated universes, from which we generated more than 3,000 simulated Dark Energy Survey dark matter maps," Jeffrey told **All About Space** magazine.

Straight away, this made the whole process a far easier task. "In the traditional way of doing these analyses, physicists have to write down an equation that

DARK ENERGY BY NUMBERS

Edwin Hubble confirmed the universe was expanding in

1929

The first direct evidence came in

1998

via observations of supernovae

Dark energy accounts for

70%

of the universe's total energy and matter

Dark matter makes up

25%

of the universe

Ordinary matter is just

5%

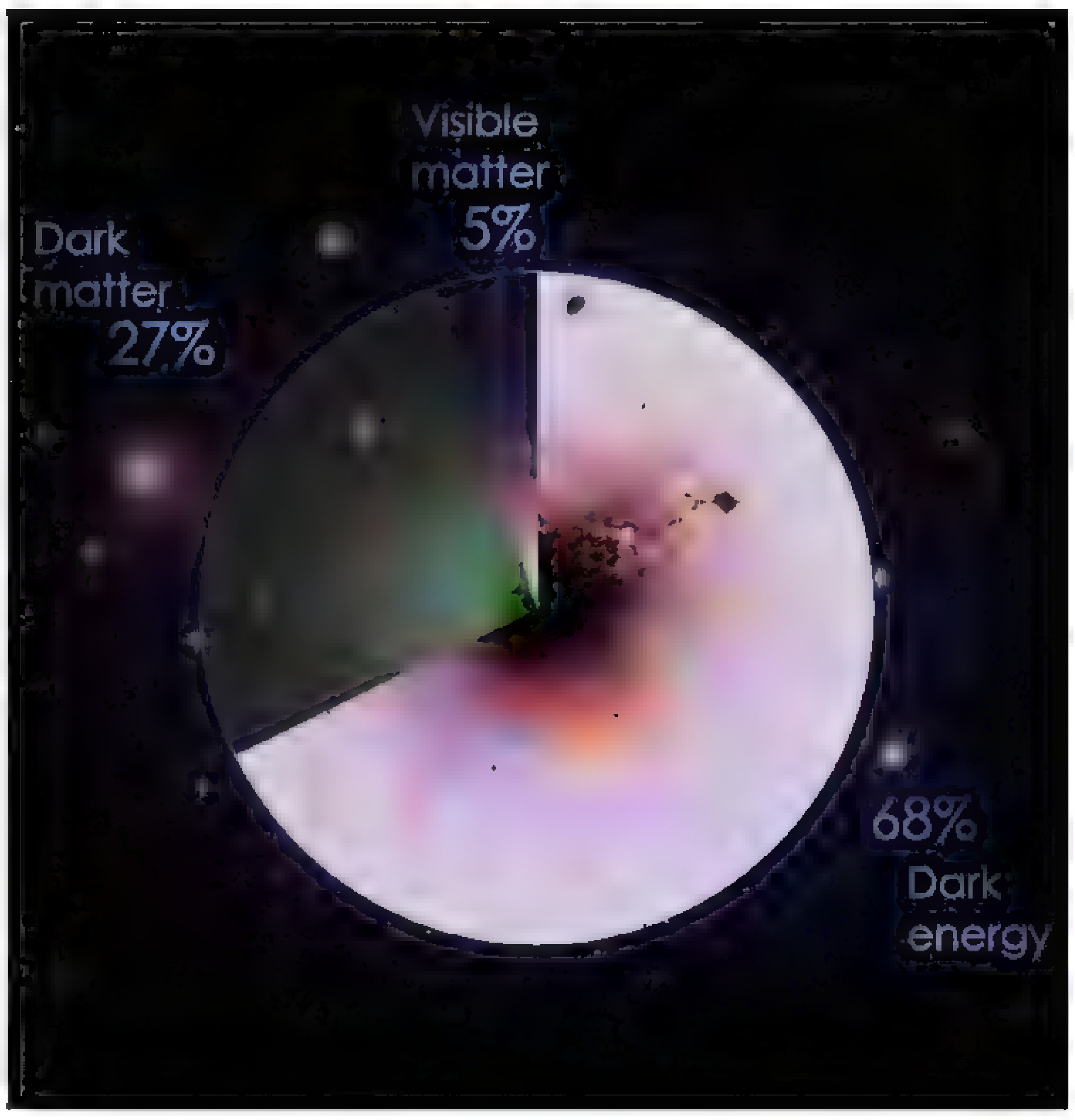
Dark energy might be a fifth element called quintessence

describes how data might look, but this can be very difficult," Jeffrey says. "AI can do something that humans do intuitively: see patterns in data. For example, a human or AI system can easily recognise a person's face, but it's very difficult to write down an equation for a face. We knew an AI system should be able to understand more about the universe from looking at a dark matter map than we could manage without it."

One of the upsides of using an AI system is that the team were able to increase the precision of their estimates of key properties of the universe by a factor of two. This enabled them to get the same results as if they were using three more maps. Without the use of AI, Jeffrey reckons that they would have needed to map another 300 million galaxies from different patches of the sky.

But how does it work? "We train the AI system by showing it examples of dark matter maps that we generated from thousands of simulated universes," Jeffrey explains. "Each simulated universe had different amounts and behaviours of dark energy. One AI system was tasked to estimate the dark energy properties from looking at the simulated maps. A second AI system was then tasked with converting those estimates into reliable odds – for example, 10:1 that dark energy is like this or that. This second step is essential for scientists, but is not usually a priority for AI problems. We need to know how well we know what we know."

One of the questions asked by researchers studying dark energy is whether or not it's a cosmological constant, as proposed by Albert Einstein. This concept was born from the theoretical physicist's belief that the universe is static – a state his theory of general relativity appeared to be at odds with. By introducing the cosmological constant, represented by the Greek letter lambda, he was able to balance the effects of gravity and show that general relativity still applied. Later, when astronomer Edwin Hubble showed the universe was indeed expanding, he put the cosmological constant down as a mistake. But was it?



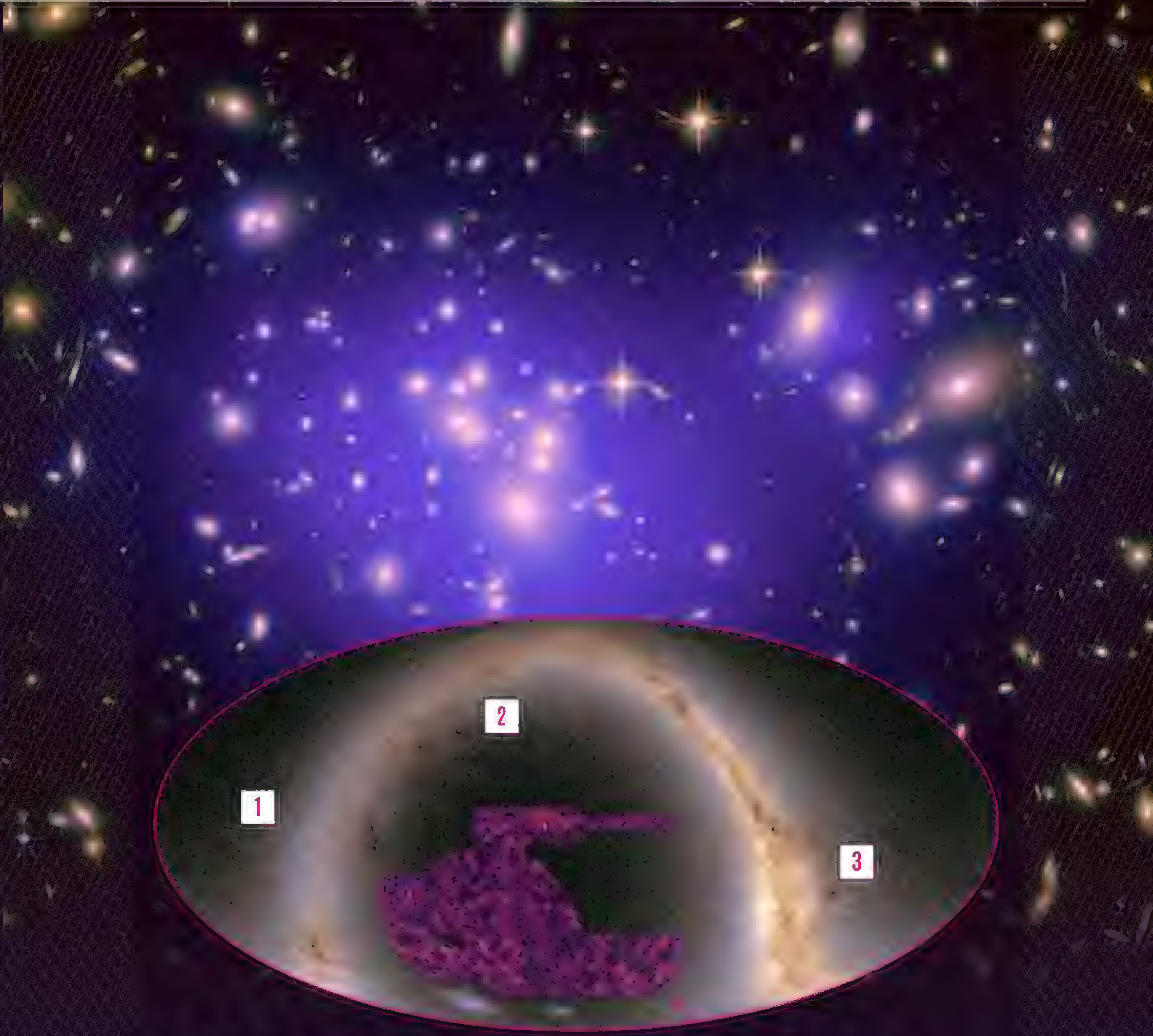
A pie chart showing the distribution of matter and energy in the universe

Powerful supercomputers in Cambridge and Edinburgh were used in the study

The cosmological constant was revised decades later when it emerged that the universe was not only expanding, but accelerating. It was reinterpreted as the energy density of empty space that overwhelms gravity. While it's still problematic – some quantum mechanics experts would have thought that the cosmological constant is greater than dark energy by some 120 orders of magnitude – the findings of the AI-driven study appear to validate it. "The study is complementary to analysis of the oldest light in the universe: the cosmic microwave background (CMB)," Jeffrey explains. "Similar to that CMB analysis, we find that dark energy appears to be consistent with Einstein's cosmological constant. However, it's not certain, and there's still a real possibility that properties of dark energy could vary with time."

The findings also suggest that matter in the universe is not as lumpy as Einstein's theory of general relativity predicts, which subsequently suggests the standard cosmological model is wrong. Instead it's more smoothly spread, and that observation ties in with previous analysis of the Dark Energy Survey map, Jeffrey says, showing that dark matter isn't necessarily made up of slow-moving exotic particles clumping together gravitationally. "Our findings are in line with the current best prediction of dark energy as a cosmological constant whose value does not vary in space or time," says Lorne Whiteway, another key member of the team and a co-author of the paper. "However, they also allow flexibility for a different explanation to be correct. For instance, it still could be that our theory of gravity is wrong."

In that sense, AI can play multiple roles. It can help spot patterns more quickly than



MAPPING DARK MATTER

How the Dark Energy Survey created a map of dark matter

1 Light distortion

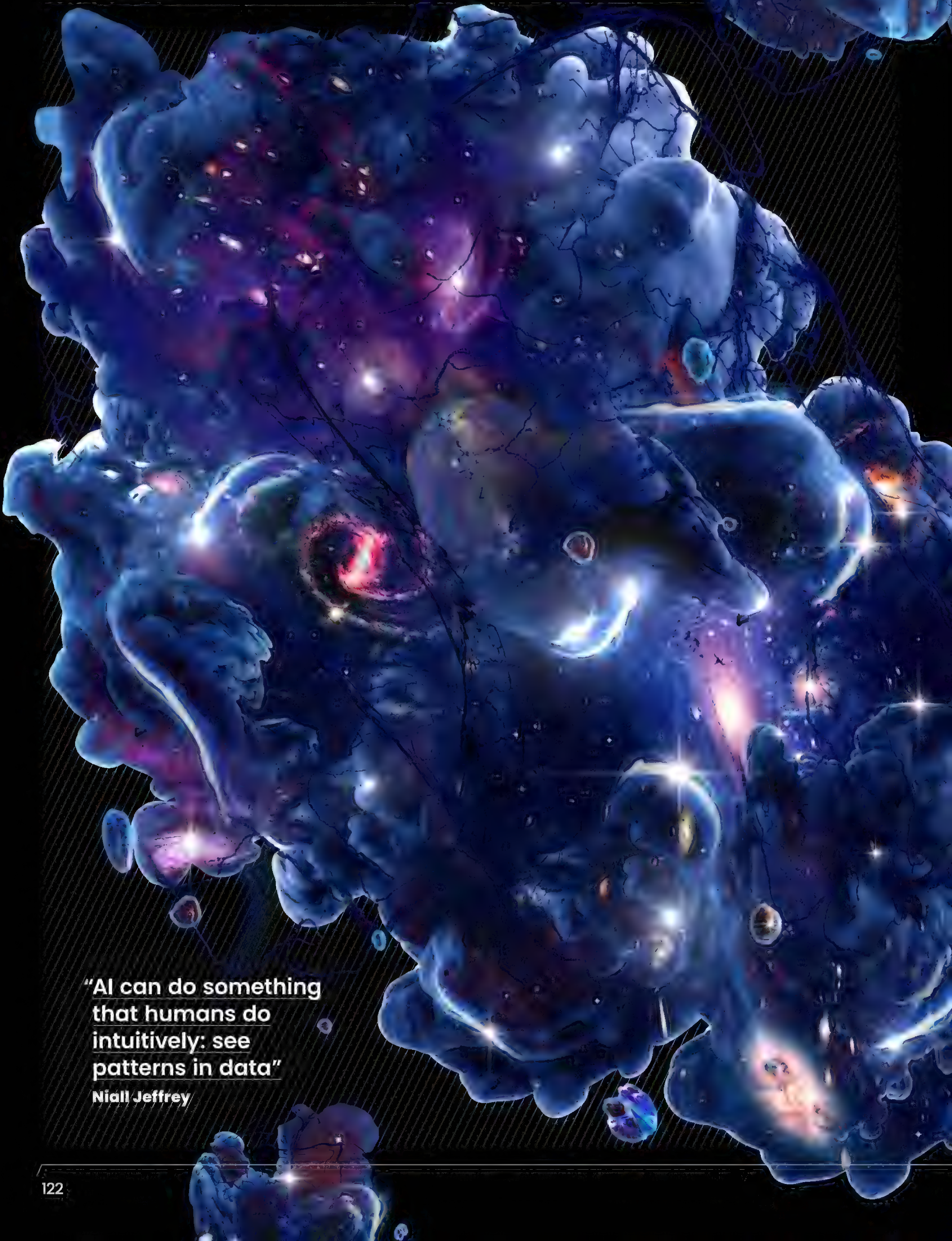
To map the existence of dark matter, astronomers looked for the distortion of light travelling to Earth from distant galaxies, measuring the galaxy shapes. This involved more than 400 scientists from 25 global institutions.

2 AI intervention

Artificial intelligence methods were used to analyse the images of 100 million galaxies to see if they had been stretched. A map of all matter detected in the foreground of those galaxies was created and released in 2021.

3 Powerful imaging

The Dark Energy Survey took images of the night sky using the 570-megapixel Dark Energy Camera, located in Chile, over the course of six years, from 2013 to 2019. It shows the universe's evolution over 7 billion years.



"AI can do something that humans do intuitively: see patterns in data"

Niall Jeffrey

humans, it can point towards particular scenarios and it can be used to test if a theory is on the right track. What's more, Jeffrey's use of AI isn't new. AI is being used as a tool across science, and there's a chance it will play a central role in helping identify meaningful trends in large datasets, generate hypotheses and simulate experiments. Making research more productive is important and could herald an era of fresh breakthroughs.

In regards to dark energy, AI is able to grant a more precise understanding, and there's every chance that the mystery could be solved sooner rather than later. "The aim is that by measuring the properties of dark energy, it will make it possible to find a theoretical explanation of what dark energy is," says Jeffrey. "With 95 per cent of the universe being dark energy and dark matter, we need to explain what is going on!"

One thing's for sure, Jeffrey is going to continue down this path, making use of AI in his work and encouraging others to do the same. But it's important to distinguish the scientific flavour of AI from the likes of ChatGPT. Those ones are prone to making stuff up, and that simply wouldn't do in terms of science. It's important that scientists have faith in the system, and that means they need to be hugely robust. There's a sense we are just at the beginning.

"AI for science has a very particular flavour," Jeffrey affirms. "Scientists do not want something that looks good or seems realistic – we need to be confident in what we have learned. A lot of my own research in AI is focused in this area – generating more realistic 'fake' simulated universes and also turning the outputs from AI methods into reliable probabilistic 'odds' that can be used by the scientific community." With more and more data being amassed, AI could really come into its own.

AI is also being used to look at data from the Dark Energy Spectroscopic Instrument (DESI) on the Mayall Telescope on top of Kitt Peak in Arizona, which has plotted the precise distance measurements of 6 million galaxies, thereby accurately plotting galaxy positions. The aim of DESI over its five years of operation is to create a 3D map of the positions and velocities of 40 million galaxies to check how dark energy is evolving with time, and AI analysis could spot important patterns.

Already, the potential has been noted, with researchers at the University of the Andes in Colombia having looked at applying data mining, machine learning and deep learning to analyse the data from DESI's ongoing observations. "We successfully achieved using AI techniques in three important aspects for DESI: assessing the quality of the data generated by the experiment, describing the cosmic web pattern on the DESI maps and predicting the redshift observed by DESI from the features observed in imaging data," co-authors Suárez Pérez and John Fredy wrote.

In that sense, scientists are backing a belief long held by theoretical physicist and cosmologist, Stephen Hawking, that computers and machine learning can be used for good. Although he did warn that AI "could spell the end of the human race," he also suggested that it may be able to better comprehend the cosmos. With scientists and AI working in tandem, the deepest, darkest mysteries are tantalisingly within reach.

David Crookes

Science and technology journalist

David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.

WHAT IS DARK ENERGY?

No one can say for certain, we just know it exists

Something sourced from black holes

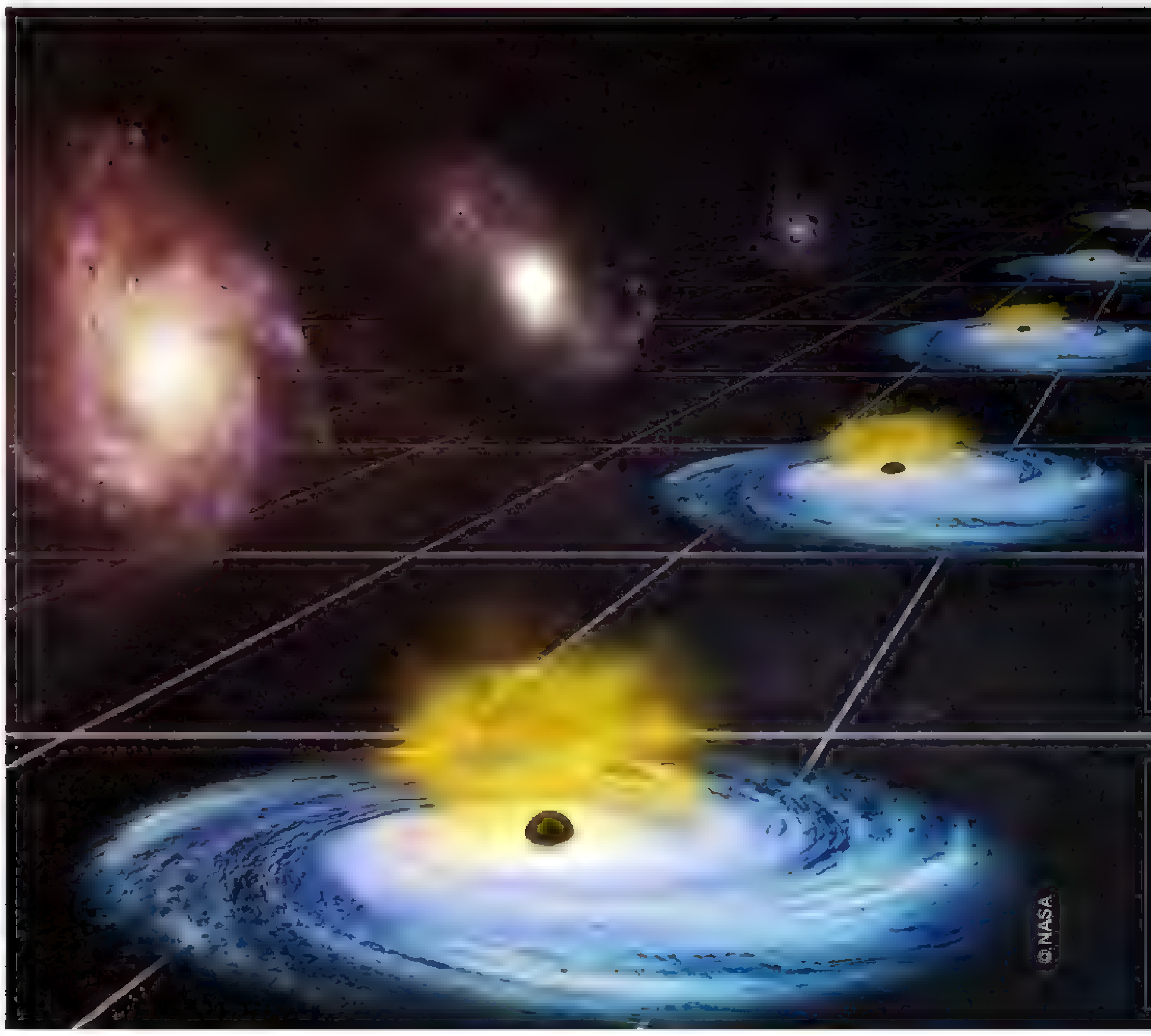
There's a chance that we simply have gravity all wrong – that we need to reconsider our understanding of it so that it's not being shoehorned into general relativity and Einstein's theory of gravity. But observations of supermassive black holes in 2023 suggest they – along with gravity – are the source of dark energy.

A sign of a fifth element

Perhaps dark energy is a fifth fundamental force that changes over time, becoming stronger. This would put it at odds with suggestions it's a cosmological constant. Some scientists suggest this element – quintessence – is an energy field filling space; others say it may be a combination of dark energy and dark matter.

It is vacuum energy

Maybe it's a theoretical background energy in space equal to the cosmological constant, thereby fitting in with Einstein's theory of general relativity. If so, then this would be pushing space outward – the larger the volume of space, the more dark energy is present. Of all of the theories, this one seems to have the most weight.



Dark energy may have varied over cosmic time, according to various studies

150 GREATEST DISCOVERIES OF ALL TIME

AS PICKED BY NASA, THE ESA AND THE WORLD'S TOP SPACE ORGANISATIONS

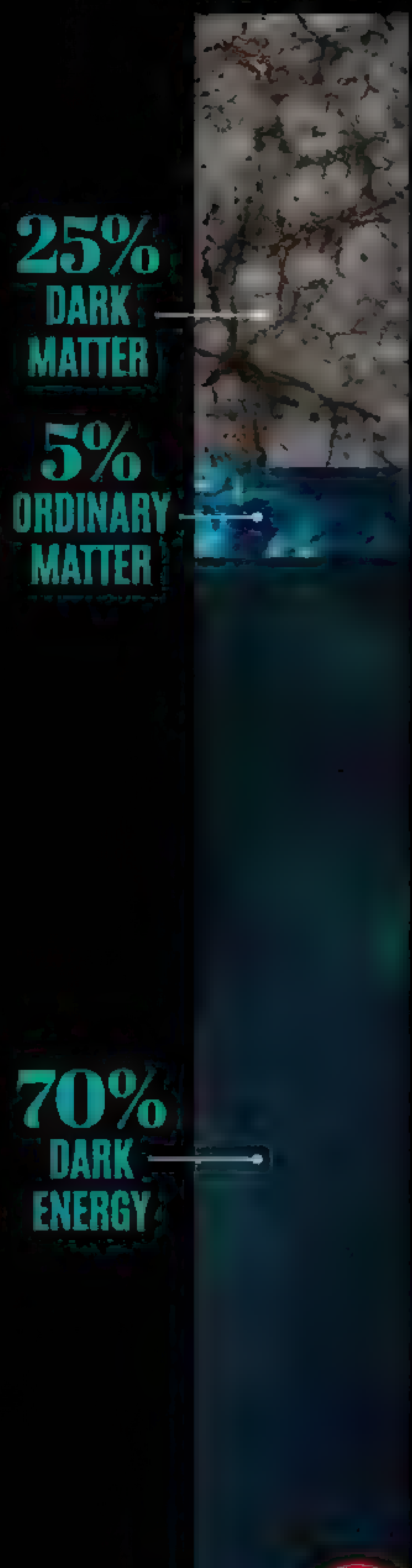
From black holes to neutron stars, tiny moons to massive planets and violent outbursts to matter that defies light, our knowledge of space has burgeoned since the 1600s, with what follows merely the tip of the iceberg in that outstanding voyage of discovery

Written by Robert Lea

SUPPLIED BY NASA **[N]**, European Space Agency **[ESA]**, European Southern Observatory **[ESO]**, All About Space magazine **[AAS]**, National Science Foundation's NOIRLab **[NOIR]**, Universidad Nacional de Colombia **[UNC]**, Princeton University **[PU]**, International Gemini Observatory **[IGO]**, University of Sussex **[UoS]**, Event Horizon Telescope **[EHT]**, Northwestern University **[NU]**, Indian Space Research Organisation **[ISRO]**, Caltech **[C]** Instituto de Astrofísica de Canarias **[IAC]**, LIGO **[L]**, International Astronomical Union **[IAU]**, Cardiff University **[CU]**, Sodankylä Geophysical Observatory **[SGO]**, University of Oxford **[UoO]**, North American Nanohertz Observatory for Gravitational Waves **[NANO]**, Sussex University **[SU]**

150

THE UNIVERSE IS STILL MYSTERIOUS



NOIR Scientists determined the energy and matter content of the universe, discovering that the 'everyday matter' made of atoms – themselves composed of protons and neutrons – accounts for just five per cent of the 'stuff' in the cosmos. That means everything we see on a day-to-day basis is just a drop in the cosmic ocean, with the rest composed of dark matter, accounting for around 25 per cent, and dark energy, accounting for a whopping 70 per cent.

Despite all of our advancements and discoveries in the name of science, we still have no idea what 95 per cent of the universe is. One of the reasons this is so important to know is that dark energy pushes galaxies apart on a large scale, almost like an 'antigravity', while dark matter seems to act to hold them together both internally and in galactic clusters. Understanding this cosmic tug-of-war is key to knowing how the universe will continue to evolve, how it will eventually end and if this could be a 'Big Rip' scenario in which the fabric of space-time itself shreds.

AAS

149

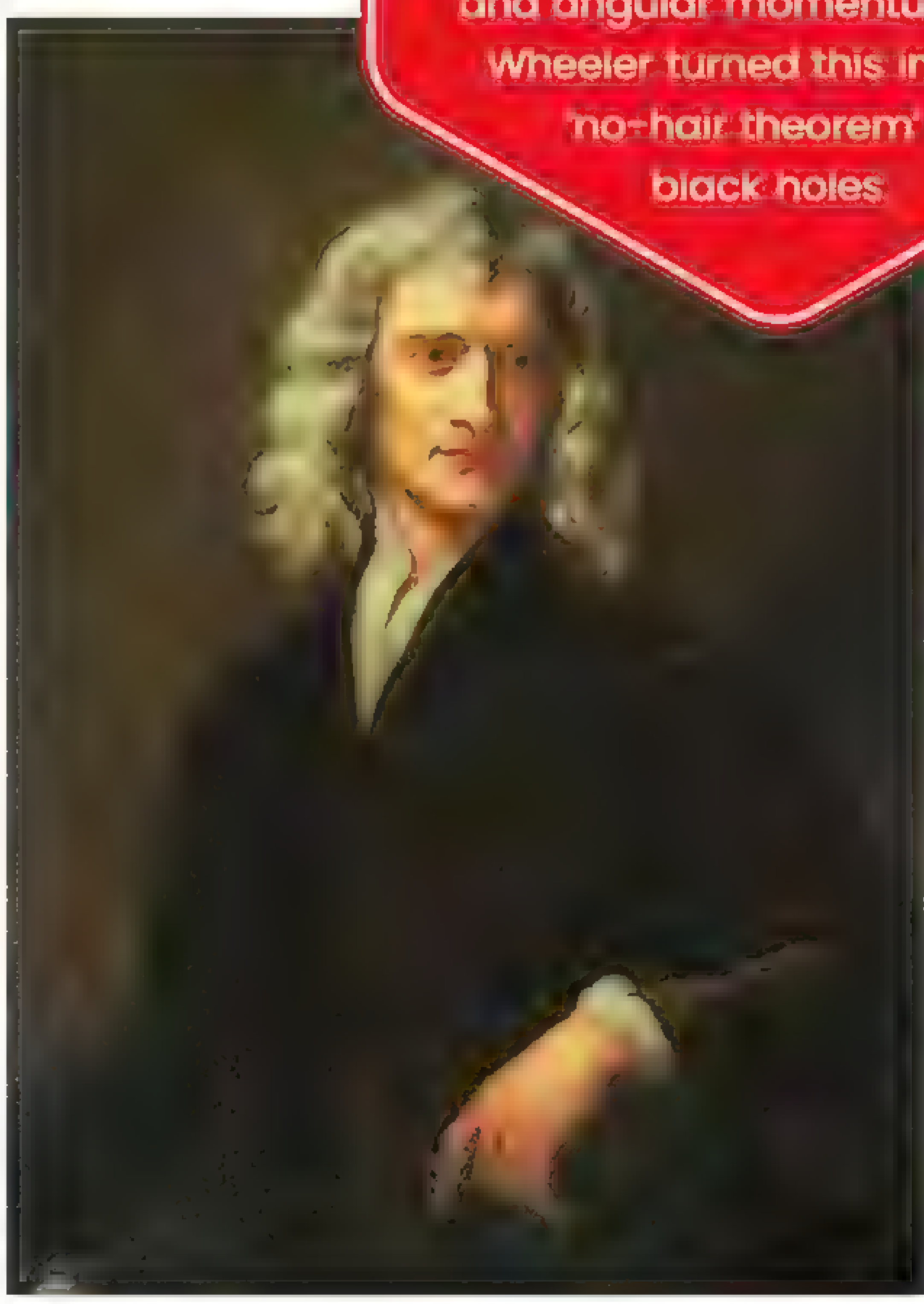
BALD BLACK HOLES

In 1967 Werner Israel theorised that black holes are simple and can be described by three characteristics: mass, charge and angular momentum. John Wheeler turned this into his 'no-hair theorem' of black holes.

148

NEWTON'S LAWS OF GRAVITY

N Formulated by Isaac Newton in 1687, Newton's law of gravitation revolves around the statement that any particle of matter in the universe attracts any other with a force, the strength of which varies as a product of their masses and inversely varies as the square of the distance between the masses increases. Though Einstein expanded on this and showed that gravity isn't a force, without this development, many of the discoveries listed here wouldn't have been possible. Unfortunately, the story of Newton being inspired by an apple falling on his head is very likely apocryphal.



147

PUSH IT TO THE LIMIT

AAS Subrahmanyan Chandrasekhar calculated the dividing line between a star that can go supernova and one that can't, determining that a star would need 1.4 times the mass of the Sun when it runs out of fuel to explode and leave a supernova in its wake. This is the Chandrasekhar limit.

146

THE SUN WILL NEVER GO SUPERNOVA

AAS One consequence of the Chandrasekhar limit is that astronomers can be pretty sure that our star, the Sun, will never go supernova. That means our star will end its life as a smouldering white dwarf – a stellar remnant.

145

THE FIRST WHITE DWARF DISCOVERY

AAS The first example of a white dwarf star was discovered on 31 January 1783 by William Herschel. The white dwarf 40 Eridani B is part of a three-star system with a second white dwarf, discovered in 1862.

144

VAMPIRE WHITE DWARFS BLOW THEIR TOPS

AAS A white dwarf star may be the end stage for the Sun, but some dead stars can spring back to life if they are feeding on material from a companion star, eventually erupting in a Type Ia supernova explosion.

143

LET THERE BE LIGHT

AAS In 1672, Newton separated white light into its constituent wavelengths, discovering that colours are the result of variations in wavelength and frequency. This breakthrough became vital in understanding the composition of stars and planetary atmospheres via a technique called spectrometry.

142

THE BIRTH OF A GAS GIANT

The realisation that Jupiter is composed of mainly gas can be traced back to 1690, when Italian-French astronomer Giovanni Domenico Cassini first noticed that the atmosphere of the planet undergoes differential rotation – different zones across the planet rotate at different speeds – suggesting it isn't a solid body. Between 1932 and 1955, scientist W. R. Ramsey began theorising that because of its low density, Jupiter may be a giant body consisting mainly of hydrogen gas, which becomes metallic at high pressures and high temperatures. This suggested that not all planets in the Solar System, and eventually beyond, are rocky like Earth.

141

LIFE CYCLE OF A STAR

The Hertzsprung-Russell diagram charting the relationships between various stellar characteristics began to take shape in 1911 as astronomers began to realise that some of the variety they see between stars is the result of viewing them in the different stages of their evolution.

140

BEST OF BOTH WORLDS

A gravitational wave breakthrough came in August 2017 when astronomers made the first and only detection of both gravitational waves and light from an event – the merger of neutron stars 130 million light years away. "The coincident discovery of gravitational and electromagnetic radiation from the merger of two neutron stars impacted numerous fields in astronomy," then-Northwestern University PhD student, Jillian Rastinejad, told **All About Space** magazine. "This event provided a new path to testing the rate of the expansion of the universe, identified the previously unknown origin of many of the heavy elements and confirmed the long-held hypothesis that neutron star mergers produce short gamma-ray bursts."

139

FAST RADIO BURST DETECTED

The first fast radio burst, a rapid blast of radio waves lasting between seconds and microseconds, was found by Duncan Lorimer in archival data in 2007. It's officially called FRB 010724, but is less formally known as the Lorimer Burst.

138

FAST RADIO BURSTS REPEAT

In 2012, astronomers discovered that one of these bursts of radio waves wasn't a one-off – it repeated. The discovery of FRB 121102 complicated the search for fast radio burst sources, suggesting astronomers had to find two causes, not one.

137

A CLUSTER OF REPEATING FAST RADIO BURSTS

In April 2023, astronomers doubled the number of known repeating fast radio bursts from 25 to 50 using the Canadian Hydrogen Intensity Mapping Experiment, hinting that many single-burst fast radio bursts may be repeaters if we watch them long enough.

136

SPACE HAS A TEMPERATURE

Thanks to the discovery of the cosmic microwave background, scientists know that even in the emptiest regions of space, the temperature is -270.5 degrees Celsius (-454.9 degrees Fahrenheit), or a few degrees above absolute zero – the coldest possible temperature, at which molecular movement stops.

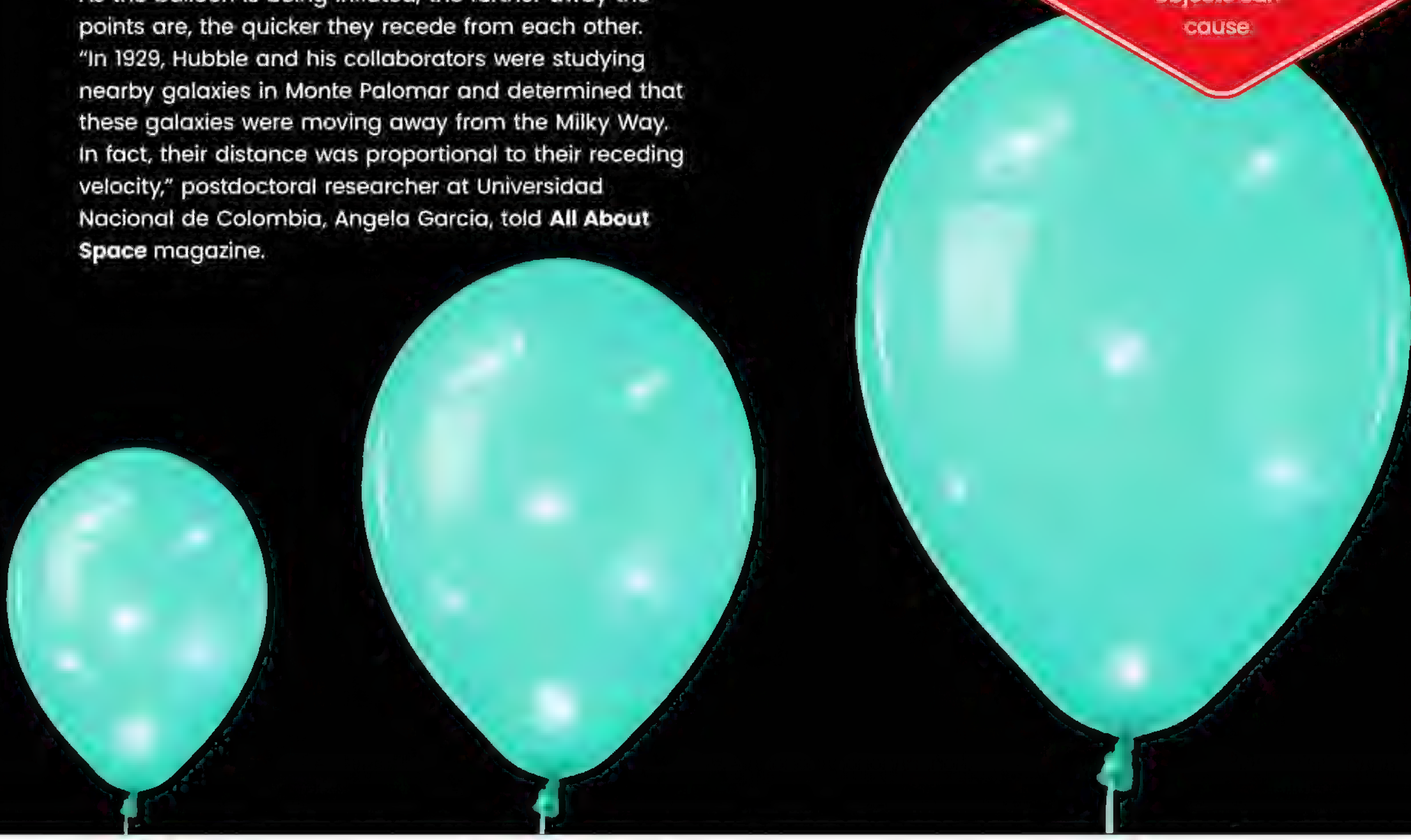
135

BUT SOME PARTS ARE COLDER...

In the 1980s, Australian astronomers discovered the Boomerang Nebula. It's the coldest object in the universe with a temperature of around -272 degrees Celsius (-457.6 degrees Fahrenheit), or just above absolute zero.

134
THE EXPANDING UNIVERSE

In 1929, using redshift, Edwin Hubble discovered that distant galaxies are receding away from each other. Additionally, the famous astronomer found that the further apart these galaxies and the Milky Way are, the more rapidly they recede from each other. This led scientists to realise that the universe is expanding. Think of this as being like points drawn on a balloon. As the balloon is being inflated, the further away the points are, the quicker they recede from each other. "In 1929, Hubble and his collaborators were studying nearby galaxies in Monte Palomar and determined that these galaxies were moving away from the Milky Way. In fact, their distance was proportional to their receding velocity," postdoctoral researcher at Universidad Nacional de Colombia, Angela Garcia, told **All About Space** magazine.



133
SPACE ROCK GOES BOOM

Onlookers captured stunning footage of a meteor entering Earth's atmosphere over the Southern Ural region in Russia on 15 February 2013, exploding at an altitude of about 30 kilometres (18.5 miles). The 18-metre (59-foot) space rock caused a bright flash and blast equal to the detonation of 400 to 500 kilotonnes of TNT. The blast injured 1,491 people and damaged as many as 7,200 buildings across six cities, showing the devastation such objects can cause.

132
EARTH ISN'T FLAT

In the 3rd century BCE, protoscientists calculated the shape of the Earth, determining that it is a sphere. This has now been proven.

131
A HISTORY OF EXTINCTION

Via fossil records, scientists found our planet has a long and rich living history; most of the creatures that preceded us are gone, some wiped out in disastrous extinction events.

130
AN ASTEROID KILLED THE DINOSAURS

In 1825, scientists discovered that the dinosaurs died out suddenly with three-quarters of life on Earth. It was soon theorised this was the result of an asteroid – the Chicxulub impactor.

129
THE SOLAR SYSTEM'S VIOLENT PAST

In the 1960s, scientists realised asteroid impacts on Earth and other planets were more frequent around 4 billion years ago during the Late Bombardment Period.

128
THE FIRST CELESTIAL CATALOGUE

In 1774, Charles Messier created a prototype version of his catalogue of deep-sky objects that became the Messier catalogue, with many galaxies still bearing the prefix 'Messier'.

127
COLD VOLCANOES

In 2010, scientists discovered that Saturn's moon Titan has volcanoes that spray ice instead of lava, showing the real variety of conditions in the Solar System, even among its many moons.

126

BLACK HOLES AREN'T JUST THEORY ANY MORE

After springing forth from Einstein's theory of general relativity, black holes remained purely theoretical until scientists spotted Cygnus X-1 in 1971, which was confirmed to be a stellar-mass black hole in 1990.

125

SUPERMASSIVE

Black holes display a vast disparity in mass. The first stellar-mass black hole ever found has 15 solar masses, but the black hole at the heart of Messier 87 was found to be billions of solar masses. The classification of supermassive black holes was born.

124

BLACK HOLES ARE MESSY EATERS

The discovery of the gargantuan black hole at the heart of Messier 87 also showed that some black holes voraciously consume the matter around them, leaving wreckage that can be blasted out in near-light-speed jets emitting powerful radiation, classed as active galactic nuclei called quasars.

123

THE VAN ALLEN BELTS

Scientist James Van Allen and his team at the University of Iowa discovered that Earth is surrounded by radiation belts, now called the Van Allen belts – a vital zone in human space exploration.

122

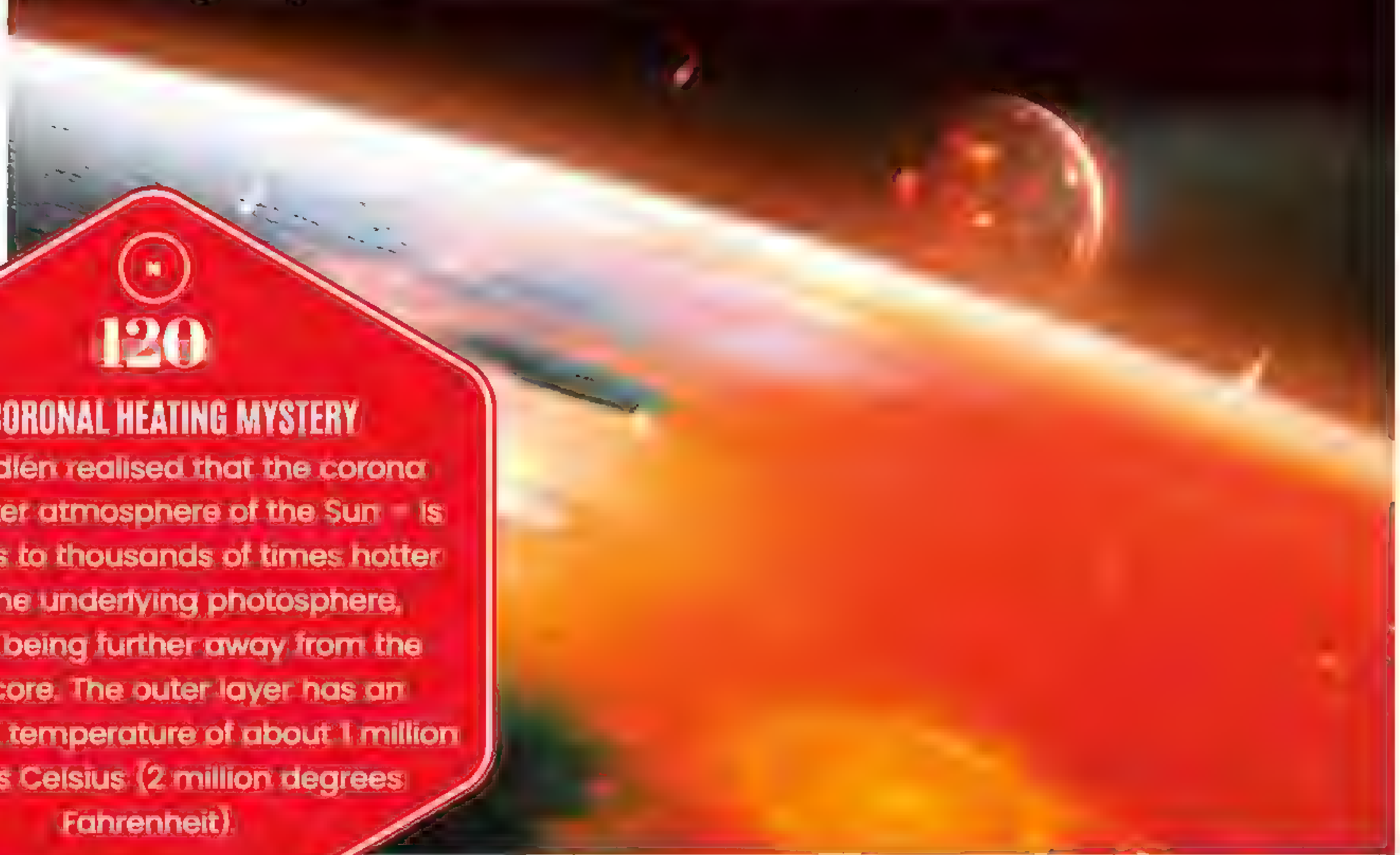
SOMETHING'S MISSING IN OUR RECIPE OF THE UNIVERSE

In 1933, Swiss astrophysicist Fritz Zwicky built on the work of others to determine that some matter is missing in our recipe of galaxies – he termed this 'dunkle Materie', or dark matter.

121

THE MOON'S VIOLENT BIRTH

First suggested by George Darwin in 1898, the giant-impact theory is the idea that the Moon was formed when the infant Earth was smashed by a Mars-sized planet called Theia. The massive spray of material blasted away from Earth by this massive collision eventually cooled and reformed as a single body – the Moon. This theory is supported by the chemical analysis of Moon rocks returned by Apollo 11 in 1969, which showed the Moon has a similar chemical composition to Earth. Though this is currently the most widely accepted theory of how the Moon was born, there are other ideas, such as 'fission theory'. This suggests that Earth once spun so fast it flung away molten material that would later form the Moon.



120

THE CORONAL HEATING MYSTERY

Bengt Edlén realised that the corona – the outer atmosphere of the Sun – is hundreds to thousands of times hotter than the underlying photosphere, despite being further away from the Sun's core. The outer layer has an estimated temperature of about 1 million degrees Celsius (2 million degrees Fahrenheit).

119

THE SHAPE OF THE MILKY WAY

In 1785, William Herschel and his sister, Caroline, attempted to determine the shape of our galaxy, and concluded it to be a disc or wheel shape. The spiral shape of the Milky Way was confirmed by the Spitzer Space Telescope in 2005 after astronomers analysed over 400 hours of observational data. The Milky Way is now theorised to be a barred-spiral galaxy around 105,700 light years across with two main spiral arms – the Scutum-Centaurus and Perseus arms – that both extended out from a thick, rotating central bar at the heart of the Milky Way. Our galaxy also possesses two less distinct arms, Norma and Sagittarius.

118
SOLAR CYCLE
AAS German amateur astronomer Heinrich Schwabe observed the Sun between 1826 and 1843, watching sunspot activity change. From this he determined the 11.5-year solar cycle.

117
FLARING UP
AAS In 1859, Richard C. Carrington and Richard Hodgson simultaneously observed solar flares for the first time when they witnessed a flash of white light while observing sunspots.

116
DARK SPOTS ACROSS THE MOON
AAS NASA's Lunar Reconnaissance Orbiter revealed details of deep, dark craters called permanently shadowed regions on the Moon in 2013 that never see light.

115
AS THE WORLD TURNS
N Though it was known since the days of Galileo, in 1851, Léon Foucault became the first person to experimentally demonstrate that Earth turns on its axis.

114
NUCLEAR FUSION AT THE HEART OF THE SUN
N In the 1920s, Arthur Eddington suggested that the source of the Sun's energy is the fusion of hydrogen to helium at its core.

113
COSMIC LIGHTHOUSE
N Scientists discovered that pulsing stars that dim and brighten are spinning neutron stars that can rotate as fast as 700 times per second.

ESA
112
TRULY SUPERMASSIVE
One striking example of a black hole, Tonantzintla 618, was first spotted in 1957, but its nature was unknown. We now know it to have a mass of around 40.7 billion solar masses, making it the most massive black hole ever seen to this day.

111
YOU ARE STAR STUFF
ESA The matter that makes up your body comes from dying stars that scattered the material they had forged during their lifetimes. The origin of our understanding of this can be traced back to Fred Hoyle, who, between 1946 and 1954, argued that stars would at their cores perform nuclear fusion to create elements ranging from carbon to iron in mass. When element-forging stars reach the end of their fuel reserves and can no longer support themselves against the inner push of their own gravity, their cores collapse, while their outer layers are ripped apart in supernova explosions. These cosmic blasts scatter the elements that stars have synthesised over billions of years, and they are eventually incorporated into cosmic dust clouds that collapse to form the next generation of stars and their planets. And, of course, those elements are also incorporated into any living thing that may evolve on those planets. One of the most staggering things about this is that the atoms in your body likely didn't come from the same exploding star. The stars that died to give you carbon, nitrogen and oxygen may have been separated by millions of light years, and those atoms may come together just once to make you.

110

THE MOST FAMOUS COMET

The first periodic comet, and arguably the most famous comet of all, Halley's Comet, was predicted to appear in 1758 by English astronomer Edmond Halley.

109

TRACKING IT BACK

Halley's Comet was tracked back to observations over two millennia, with the comet even believed to be featured in the Bayeux Tapestry, a record of the Battle of Hastings of 1066.

108

STUDIED IN DEPTH

Halley's Comet returned to Earth in 1986, with humanity making stunning observations of the comet with an array of telescopes and spacecraft, including NASA's Pioneer 7 and Pioneer 12.

107

GOING ROGUE

Challenging our picture of planets neatly orbiting their stars, in 2012 astronomers discovered an exoplanet called CFBDSIR2149-0403 that wanders the Milky Way alone – the first confirmed rogue planet.

106

ROGUES' GALLERY

In 2021, astronomers discovered a huge family of 70 rogue planets wandering the Milky Way. This is the single largest clutch of rogue exoplanets ever seen and suggests there could be many more out there.

105

THE MONSTER AT THE HEART OF THE MILKY WAY

On 13 February 1974, a point-like source of intense radio waves was found at the heart of the Milky Way, named Sagittarius A* (Sgr A*). Reinhard Genzel and Andrea Ghez proved that Sgr A* is a supermassive compact object.

104

GALILEO DISCOVERS SATURN'S RINGS

Galileo discovered Saturn's rings in 1610, revealing one of the most extraordinary planetary features in the Solar System. The rings of Saturn are made of at least seven distance bands, which themselves consist of tiny chunks of rock and ice coated with dust. It's believed they were created when the tremendous gravity of the gas giant captured and tore apart comets, asteroids and even pieces of shattered moons. Ring systems were later discovered around the other giant planets of the Solar System – Jupiter, Uranus and Neptune, but the rings of Saturn remain the largest and most prominent ring system of the Solar System.

103

DARK MATTER IS THE MISSING INGREDIENT

In the 1970s, Vera C. Rubin and W. Kent Ford saw the stars visible within a typical galaxy only provide around ten per cent of the gravitational 'sticking power' needed to keep those galaxies from flying apart. They did this by measuring the rotational speed of galaxies and determining that they rotate so fast that the gravity of the visible matter within them wouldn't hold them together. There must be a 'hidden' mass that emits or absorbs no light, and thus can't be composed of 'ordinary' atoms. Dark matter was born, and our universe became much more mysterious.

102
VENUS IS HELL

ESA While it is often called 'Earth's twin', the second planet from the Sun is also the hottest place in the Solar System. Similar in size and structure to Earth but spinning in the opposite direction to our planet, the atmosphere of Venus traps heat and causes a runaway greenhouse effect. This drives temperatures at the surface as high as 464 degrees Celsius (867 degrees Fahrenheit), hot enough to melt lead. Additionally, the air pressure at the surface of Venus is estimated to be 75 to 100 times greater than that on Earth. As if this isn't enough, Venus's upper atmosphere is blanketed by thick clouds of sulphuric acid.

"The atmosphere of Venus traps heat and causes a runaway greenhouse effect"

AAS
101
THE MOON'S COMPOSITION
Analysing the lunar surface, scientists discovered that the Moon is 43 per cent oxygen, 20 per cent silicon, 19 per cent magnesium, 10 per cent iron, 3 per cent calcium, 3 per cent aluminium, 0.42 per cent chromium, 0.18 per cent titanium and 0.12 per cent manganese

100
MORE DWARF PLANETS...
In 2005, data collected in 2003 revealed the existence of Eris. This dwarf planet is slightly smaller than Pluto, out beyond the orbit of Neptune.

99
STARS HAVE LIMITS
N In the 1920s, solar physicists established the Eddington limit, a cap on how bright a star can get while the outward force balancing the inward push of gravity is stable.

98
THE SOLAR SYSTEM'S COOL SHELL
AAS The first of three Kuiper Belt objects was discovered by Dave Jewitt and Jane Luu in 1992, leading to the realisation there's an icy band of comets at the edge of the Solar System.

97
THE SUN'S STRANGE OUTER ATMOSPHERE
N The outermost part of the Sun's atmosphere is not usually visible due to it being washed out. Ultraviolet emissions from the corona were first detected on 10 October 1946.

96
IMPOSSIBLE RING
AAS In 2023, icy dwarf planet Quaoar, half the size of Pluto, was found to have a strange ring system further from its parent body than any seen in the Solar System before, challenging ring-formation theories.

95
GALACTIC CANNIBALISM
N Scientists find that galaxies grow by smashing together and merging, finding evidence such as stretched-out 'tidal tails' of stars and gas around other galaxies.

94
EARTH IS NOT ALONE
The Greeks discovered the five planets visible to the naked eye over Earth: Mercury, Venus, Mars, Jupiter and Saturn. They called them 'planets', which means 'wanderers' in Greek.

93
URANUS IS REVEALED
In 1781, William Herschel discovered Uranus, an ice giant and the seventh planet from the Sun. It was the first object to be classified as a planet with a telescope.

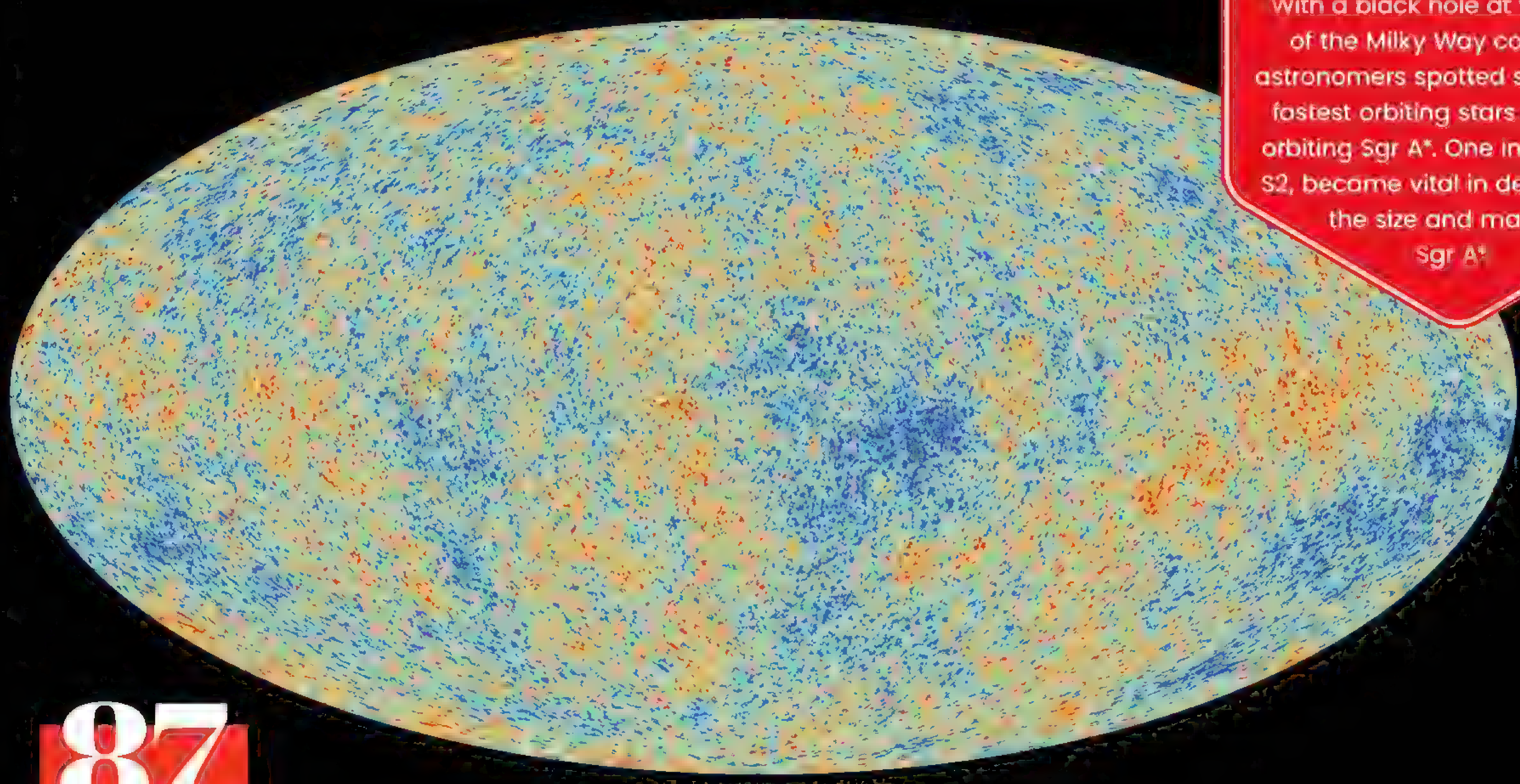
92
ANOTHER ICE GIANT
The eighth planet from the Sun, Neptune, was found by astronomers on 23 September 1846. The discovery was made by mathematically considering perturbations in the orbit of Uranus.

91
PLUTO: ONCE THE NINTH PLANET
In February 1930, Pluto was discovered at the edge of the Solar System by Clyde Tombaugh and was classified as the Solar System's ninth planet.

90
THE MAIN ASTEROID BELT MANIFESTS
18th-century German astronomer, Johann Titius, predicted the existence of a band of small bodies between Mars and Jupiter prior to his death in 1796.

89
THE FIRST ASTEROID
Giuseppe Piazzi discovered the first asteroid, Ceres, on 1 January 1801. Ceres is the largest body in the main asteroid belt and is now considered a dwarf planet – the only one in the inner Solar System.

88
SGR A* IS NOT ALONE
With a black hole at the centre of the Milky Way confirmed, astronomers spotted some of the fastest orbiting stars ever seen orbiting Sgr A*. One in particular, S2, became vital in determining the size and mass of Sgr A*



87
PIGEON POO OR COSMIC FOSSIL?
The cosmic microwave background (CMB) was discovered accidentally in 1965 by Arno Penzias and Robert Wilson using a large radio antenna in New Jersey. They initially chalked the microwave background hum filling the universe to pigeon poop on their equipment, but after clearing pigeons from the Holmdel Horn Antenna, this was eliminated. CMB radiation is a fossil left over from just after the Big Bang. The discovery won Penzias and Wilson the Nobel Prize in Physics in 1978. The CMB dates back to an event in the early universe called the last scattering. Prior to this event, the cosmos was opaque to light, with photons endlessly scattered by a soup of free electrons and thus prevented from travelling. After around 370,000 years, the universe had expanded and cooled enough to allow electrons and protons to unite and create the first atoms of hydrogen – a period called the 'Epoch of Reionisation'. As a result, photons could suddenly travel, and the universe instantaneously became transparent to light. This first light – the first free photons – is seen today as the CMB, surrounding the universe almost completely evenly.

86

HOW MARS BECAME THE RED PLANET

Since its discovery, the blood-red hue of Mars has been its defining characteristic, with it getting its name from iron being exposed to oxygen on the Martian surface.

85

SUNSPOTS BECAME CLEAR

In 1908, George Ellery Hale found that dark patches on the Sun's surface, sunspots, are connected to the twisting of the Sun's intense magnetic fields.

84

THE PEAK OF MARS EXPLORATION

In 1971, Mariner 9 discovered Olympus Mons, a mountain on Mars two-and-a-half times as large as Mount Everest – Earth's highest peak.

83

FURTHER AND FASTER THAN EVER

The Parker Solar Probe became the fastest object ever created by humanity as it raced past the Sun at 635,266 kilometres (394,736 miles) per hour on 27 September 2023.

82

SHAKING THINGS UP ON MARS

In 2019, the InSight lander detected seismic waves rippling through Mars, confirming the existence of a geological phenomenon termed 'marsquakes', which were first detected – but not confirmed – by the Viking spacecraft.

81

COLLISION COURSE

In 2012, astronomers discovered that the Milky Way and Andromeda are heading towards each other. Andromeda is 2.5 million light years away, and the two galaxies are predicted to meet in around 4 billion years, although a 2025 study questions whether this is still a certainty.

80

BLACK HOLE BIRTH PROCESSES DISCOVERED

The existence of black holes had been revealed by solutions to the equations at the heart of Einstein's general relativity, but even the great physicist wasn't entirely sure that black holes actually existed. It was in 1939 when the 'father of the atom bomb', Robert Oppenheimer, and colleagues calculated that these regions of space-time so dense and compact that they have an escape velocity greater than light itself, could be birthed by the collapse of the most massive stars. They developed a model of black hole birth that sees stars at the end of their fuel for nuclear fusion collapse, triggering a massive supernova explosion. As the outer layers are blown away in this blast, the collapsing core becomes a black hole. This model is still used today and was key to scientists really starting to seriously consider the existence of black holes.

79

GRAVITATIONAL WAVES MEASURED FOR THE FIRST TIME

Gravitational waves are tiny ripples in the fabric of space-time that Einstein predicted would arise when any body with mass accelerated. On 14 September 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo gravitational wave detectors picked up the faint signal of gravitational waves from a merger between a 36-solar-mass and 29-solar-mass black hole around 1.3 billion light years away. The signal was designated GW150914 – GW for 'gravitational wave' and the numbers representing the date of observation.

78

IMAGING THE IMPOSSIBLE

On 10 April 2019, humanity got its first look at a supermassive black hole, which took the form of a glowing ring of matter around a dark heart. The image, captured by the Event Horizon Telescope (EHT), was of the supermassive black hole at the heart of the galaxy Messier 87. Located 53 million light years away and with a mass 6.5 billion times that of the Sun, the supermassive black hole in the image is represented by a shadow falling on the glowing, hot matter that surrounds the black hole and feeds it. Humanity's first glimpse of a black hole was confirmation that black holes look almost exactly as Einstein's theory of general relativity predicts they should look.

"While we had known that black holes existed in our universe for a while, no one had seen them directly," University of Sussex theoretical physicist and black hole expert, Xavier Calmet says. "These pictures of the shadows of black holes are the closest we will ever get to a direct picture of a black hole, which otherwise appears black, as not even light can escape from behind their event horizon."

77

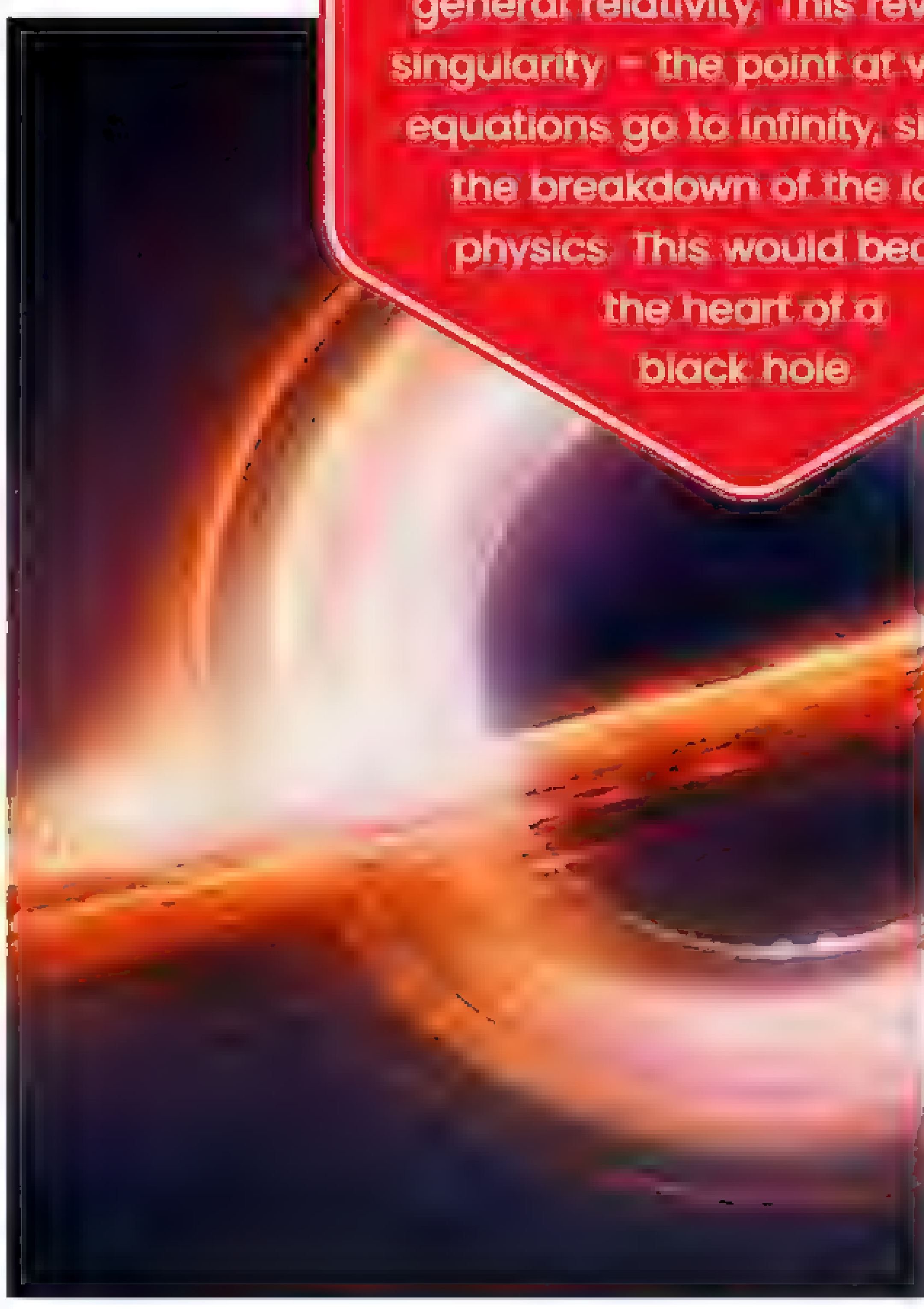
THE HEARTS OF BLACK HOLES

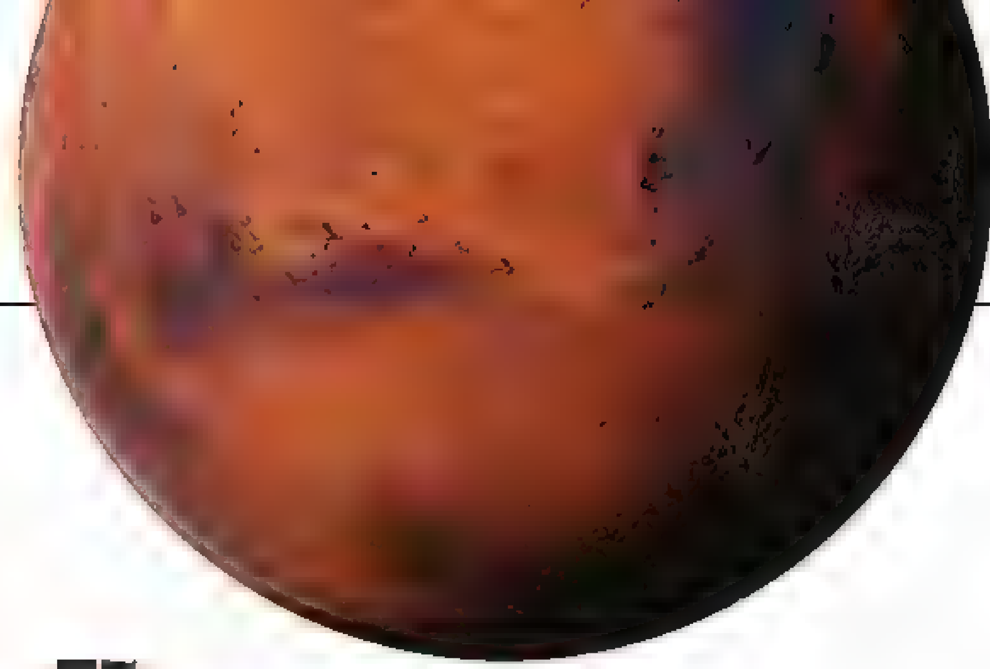
Karl Schwarzschild developed the first solution to the equations of general relativity. This revealed a singularity – the point at which the equations go to infinity, signalling the breakdown of the laws of physics. This would become the heart of a black hole

76

THE EVENT HORIZON IS BORN

While working with his solution to Einstein's theory of general relativity, German astronomer Karl Schwarzschild calculated that all astronomical bodies would have an escape velocity, known as the Schwarzschild radius. For most bodies, this radius would be deep within them, but for highly compressed massive objects like black holes, the Schwarzschild radius is outside their limits. For black holes, this is their outer boundary – the light-trapping surface known as an event horizon, before which no information can escape a black hole, which protects the mystery of the central singularity.





75

THE RIGHT STUFF

Scientists confirmed that Mars once had the right chemistry to support life as in 2013, NASA's Curiosity rover discovered sulphur, nitrogen, oxygen, phosphorus and carbon on Mars – all key ingredients necessary for life.

74

THE SOLAR WIND IS FOUND

Physicist Eugene Parker theorised in the 1950s that the Sun is surrounded by solar wind that would be visible in the solar halo during an eclipse and when its particles strike the Earth's atmosphere (the northern lights).

73

DIAMONDS ARE FOREVER

Uranus and Neptune may look like inert, blue snowballs from a distance, but the discovery that diamonds may rain through the atmospheres of the ice giants in 2017 showed they might be the most 'alien' worlds in the Solar System.

72

EXOMOONS

In January 2022, astronomers found what seems to be a moon orbiting a planet outside the Solar System. The potential exomoon orbits a Jupiter-sized planet called Kepler-1708 b and appears to be 2.6 times as large as Earth – larger than any moon in the Solar System.

71

A VERY VOLCANIC MOON

Jupiter's rocky moon Io was discovered to be the most volcanic body in the Solar System, the result of tidal forces caused by the gravity of Jupiter and the other Galilean moons squashing and squeezing it.

70
A STAR OLDER THAN THE UNIVERSE?
AAS After observing HD 140283, a star 190 light years from Earth, astronomers thought it 16 billion years old – older than the universe. It is now thought to be 14.3 billion yars old.

69
ANCIENT ECLIPSES
N Accounts of solar eclipses date back as far as 3340 BCE. Pre-Socratic Greek philosopher Anaxagoras is credited with offering the first scientific explanation.

68
TWO'S COMPANY
AAS John Michell discovered in 1767 that some stars are actually binary stars – two stars that are gravitationally bound together and orbit around each other.

67
THE MOON IS SHAKING
N Instruments placed across the lunar surface by the Apollo missions collected seismic data between 1969 and 1977, showing 'moonquakes' rock the Moon.

66
NOT ALL STARS ARE LIKE THE SUN
AAS By the early 20th century, astronomers realised stars come in different sizes, temperatures, masses and colours, with blue hotter than red and yellow.

65
THE COSMIC WEB
ESA Dark matter binds galaxies on large scales. In 1996, Richard Bond coined the phrase 'cosmic web' to describe this twisted structure of filaments and clumps formed by dark matter.

64
MARS HAS A WATERY PAST

Modern-day Mars is the template of a dry, barren and lifeless planet, defined by its dust and rock-strewn surface. But it wasn't always this way. Though it's now arid, scientists have long suspected that Mars flowed with water in its past. Confirming this, the NASA Mars rovers Curiosity and Perseverance both explored what experts believed were once overflowing bodies of water. Curiosity started exploring the 155-kilometre (96-mile) wide dry lakebed of Gale crater, estimated to be about 3.5 to 3.8 billion years old, in August 2012. Meanwhile, Perseverance was trundling through the 45-kilometre (28-mile) wide Jezero crater since February 2021, drilling free rock samples from an area believed to have been the junction of river channels almost 4 billion years ago.

The clearest evidence of water on Mars yet was delivered by the Curiosity rover in 2023 as it explored an ancient lakebed, finding ancient water ripples that stirred up sediments that left textures in rocks billions of years ago.

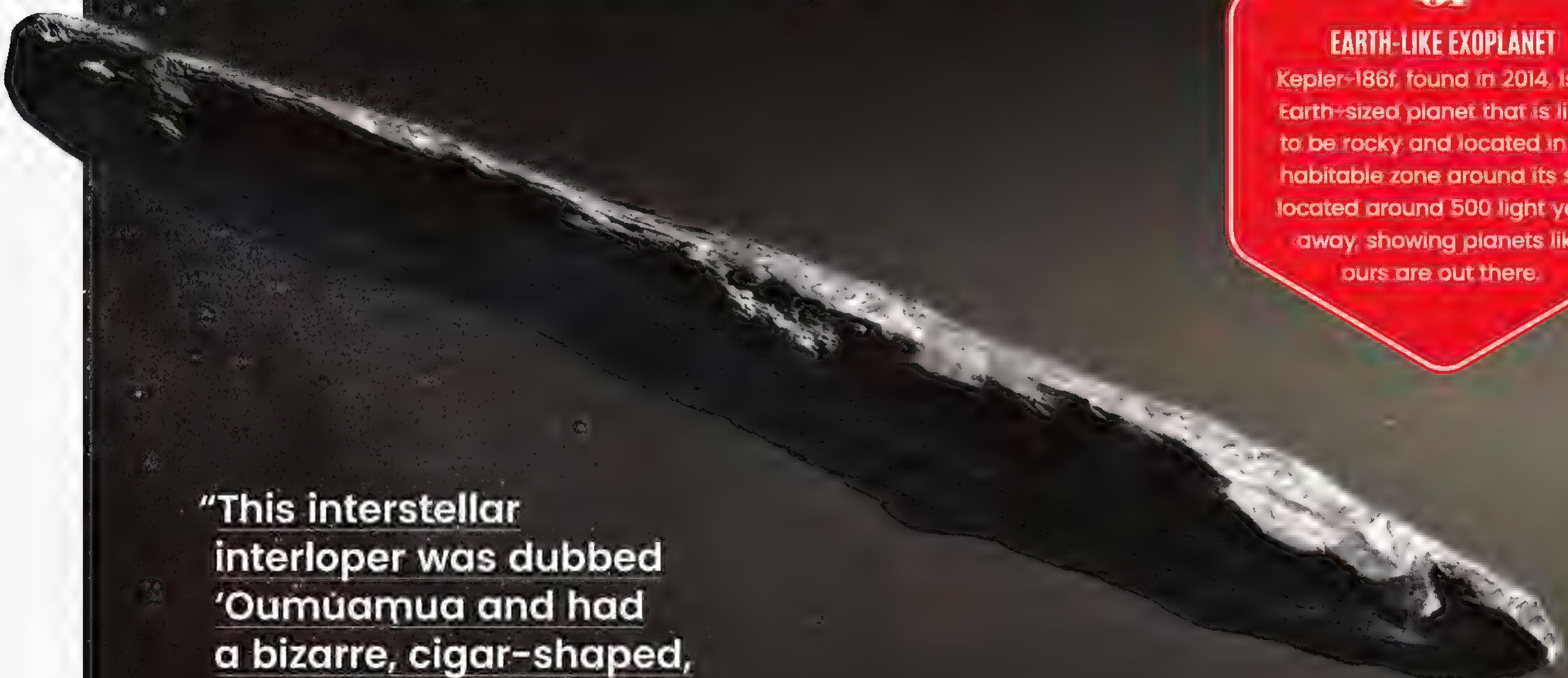
ESA
63
AN ODD-SHAPED PLANET
WASP-103 b, spotted in 2022 by the CHaracterising ExOPlanets Satellite (CHEOPS), is a planet squashed into a rugby-ball-like shape by the tidal forces generated by its star.

62

SOLAR SYSTEM INVADERS

On 19 October 2017, astronomers discovered the first known interstellar object visiting our Solar System from beyond its outer reaches. This interstellar interloper was dubbed 1I/2017 U1 'Oumuamua and had a bizarre, cigar-shaped, elongated body that still perplexes scientists. Hubble discovered a second interstellar object in 2019, this time a comet with a more traditional shape, named Comet 2I/Borisov.

'Oumuamua and 2I/Borisov are both excellent reminders of a much wider cosmos outside the Solar System, and whose presence suggests that the Solar System might contain many more extrasolar interlopers that are just waiting to be uncovered.



"This interstellar interloper was dubbed 'Oumuamua and had a bizarre, cigar-shaped, elongated body"

61

EARTH-LIKE EXOPLANET

Kepler-186f, found in 2014, is an Earth-sized planet that is likely to be rocky and located in the habitable zone around its star, located around 500 light years away, showing planets like ours are out there.

60

STELLAR NURSERIES ARE BORN

In 1610, Nicolas-Claude Fabri de Peiresc discovered the Orion Nebula – a glowing cloud of gas and dust. This is a region of active star formation and is the closest such region to Earth.

59

THE SUN HAS DEPTH

The Sun isn't just an amorphous blob of super-hot gas, it consists of six main layers: the core, radiative zone, convective zone, photosphere, chromosphere and corona.

58

THE FIRST NEUTRON STAR

In 1967, the first neutron star was detected in the form of a repeating radio signal using a large radio telescope at the Mullard Radio Astronomy Observatory by Jocelyn Bell Burnell.

57

THE MOON WAS VOLCANICALLY ACTIVE

After landing on the Moon in 1969, the Apollo 11 mission revealed that the Moon was hot when it formed and that it was magnetically active for at least 800 million years.

56

PULSATING FIND

In 1967, scientists discovered that 'pulsing stars' that periodically brighten are spinning neutron stars that sweep radiation over Earth with every pulse.

55

THE UNIVERSE IS FLAT

Earth might not be flat, but in 2003 physicist David Spergel measured tiny variations in the CMB, concluding the amounts of positive and negative energy suggest the universe is flat.

54

SUNSPOTS

N Sunspots became a gauge of the Sun's activity. In 1613, changes in the position of sunspots confirmed that the Sun rotates monthly.

53

PLANETARY MOTION

ESA From 1609 to 1619, Johannes Kepler developed his laws of planetary motion, describing the orbits of the planets as ellipses, the area these orbits cover and the link between orbital size and orbital period.

52

THE FIRST NEAR-EARTH ASTEROID

N The first near-Earth asteroid, 433 Eros, was discovered in 1898 by Carl Gustav Witt and Felix Linke at Urania Observatory in Berlin and Auguste Charlois at Nice Observatory.

51

THE BIGGER THEY ARE, THE FASTER THEY FALL.

N Massive blue stars are hotter, and thus burn their hydrogen fuel faster and 'die' faster – or, more accurately, move off the main sequence of the Hertzsprung-Russell diagram more quickly.

50

SOME ASTEROIDS FOLLOW THE LEADER

N In 1906, astronomer Max Wolf of Heidelberg-Königstuhl State Observatory discovered the Trojan asteroids; space rocks trapped in the orbit of Jupiter stuck following the gas giant around the Sun.

49

EARTH'S MAGNETIC BUBBLE

AAS Explorer 1 discovered that Earth is surrounded by a magnetic bubble called the magnetosphere in 1958. This protects the planet's surface from bombardment by energetic particles.

48

TWO EXOPLANETS AT ONCE

N For as long as we've known that distant stars are bodies like the Sun, we've theorised about the planets that may orbit them. As shocking as it may sound, until the 1990s we weren't completely sure that other stars hosted planets. That changed with the first detection of a duo of planets outside the Solar System, called extrasolar planets or 'exoplanets'. These two new worlds, called Phobetor and Poltergeist, were discovered in 1992 by Aleksander Wolszczan and Dale Frail. Both rocky planets are orbiting a rapidly spinning neutron star blasting out jets of radiation – the pulsar PSR B1257+12 is located around 2,313 light years from Earth.

47

THE BIGGEST STORM IN THE SOLAR SYSTEM

ESA The Solar System's largest storm, the Great Red Spot, could have been discovered raging across the atmosphere of Jupiter by either English scientist Robert Hooke in 1664 or by Italian astronomer Giovanni Cassini a year later. This persistent, high-pressure region of the atmosphere of Jupiter is an anticyclonic storm, given its name due to its reddy-orange hue, the cause of which is still uncertain. We now know this storm is currently 16,350 kilometres (10,159 miles) wide – 1.3 times the width of Earth. In 2021, Juno discovered the depth of this red storm, finding that it sinks at least 483 kilometres (300 miles) into the atmosphere of Jupiter.

46

SOLAR WIND MEASURED

N In 1959, the Soviet Luna 1 became the first spacecraft to directly observe the solar wind – streams of charged particles emitted by the Sun – and measure its strength.

45

FIRST COMET FOUND WITH A TELESCOPE

N Observations of comets date back to 289 BCE, but significant development in this practice occurred in November 1680, when Gottfried Kirch discovered the first comet with a telescope.

44

GALAXIES HAVE INVISIBLE HALOS

ESA Building on the work of Vera C. Rubin, scientists discovered that dark matter seems to envelope most – if not all – galaxies in halos extending well beyond their stars and gas.

43

THE SUN BLOWS ITS TOP

N The first observation of a massive outflow of stellar material from the Sun, called a coronal mass ejection (CME), was observed by Orbiting Solar Observatory 7 (OSO-7) on 14 December 1971.

42

LAGRANGE POINTS

ESA These are gravitationally stable points between two large masses, such as the Sun and Earth. Scientists now use these to 'park' satellites like the James Webb Space Telescopes around our planet.

41

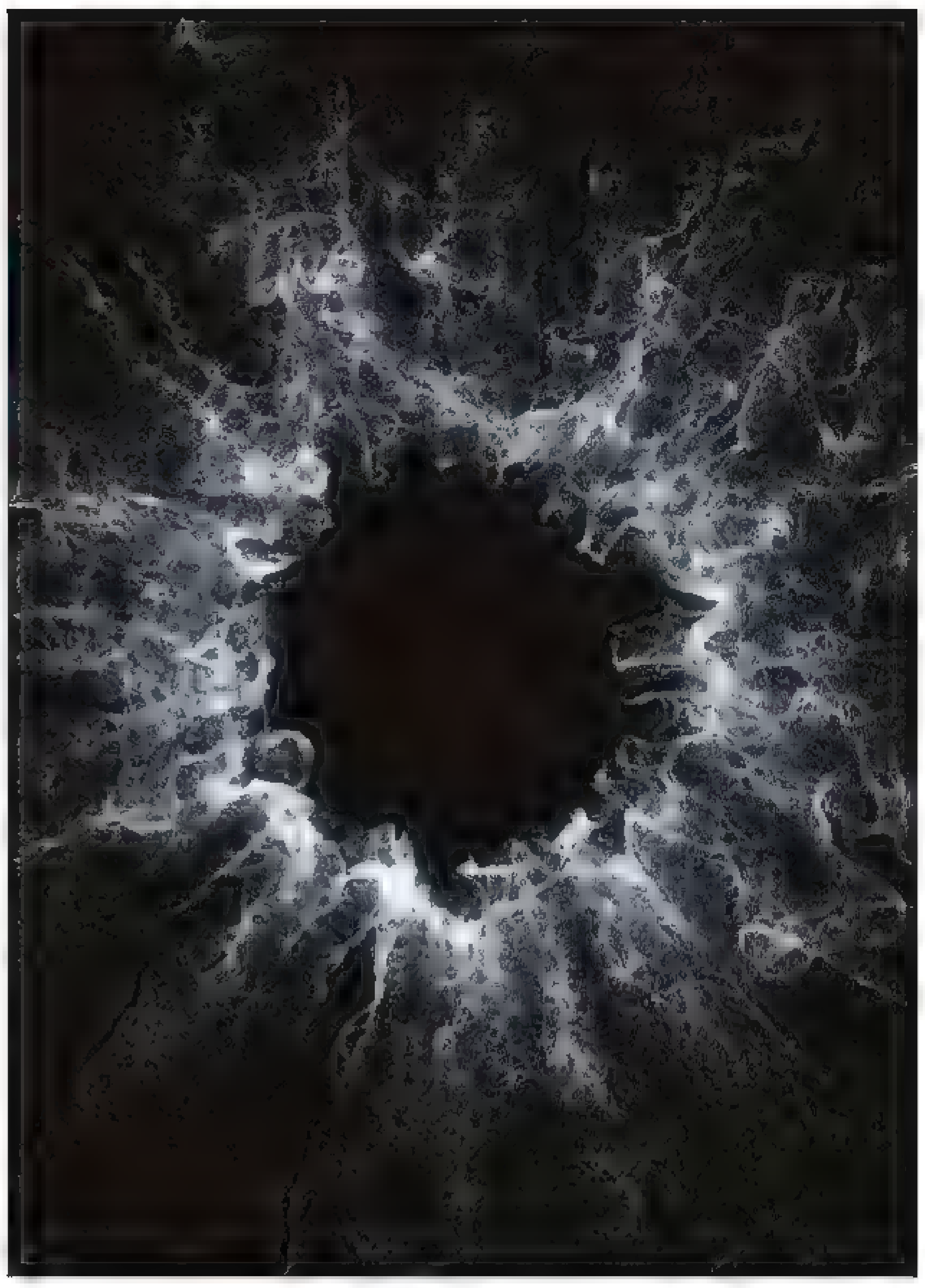
TOUCHING THE SUN

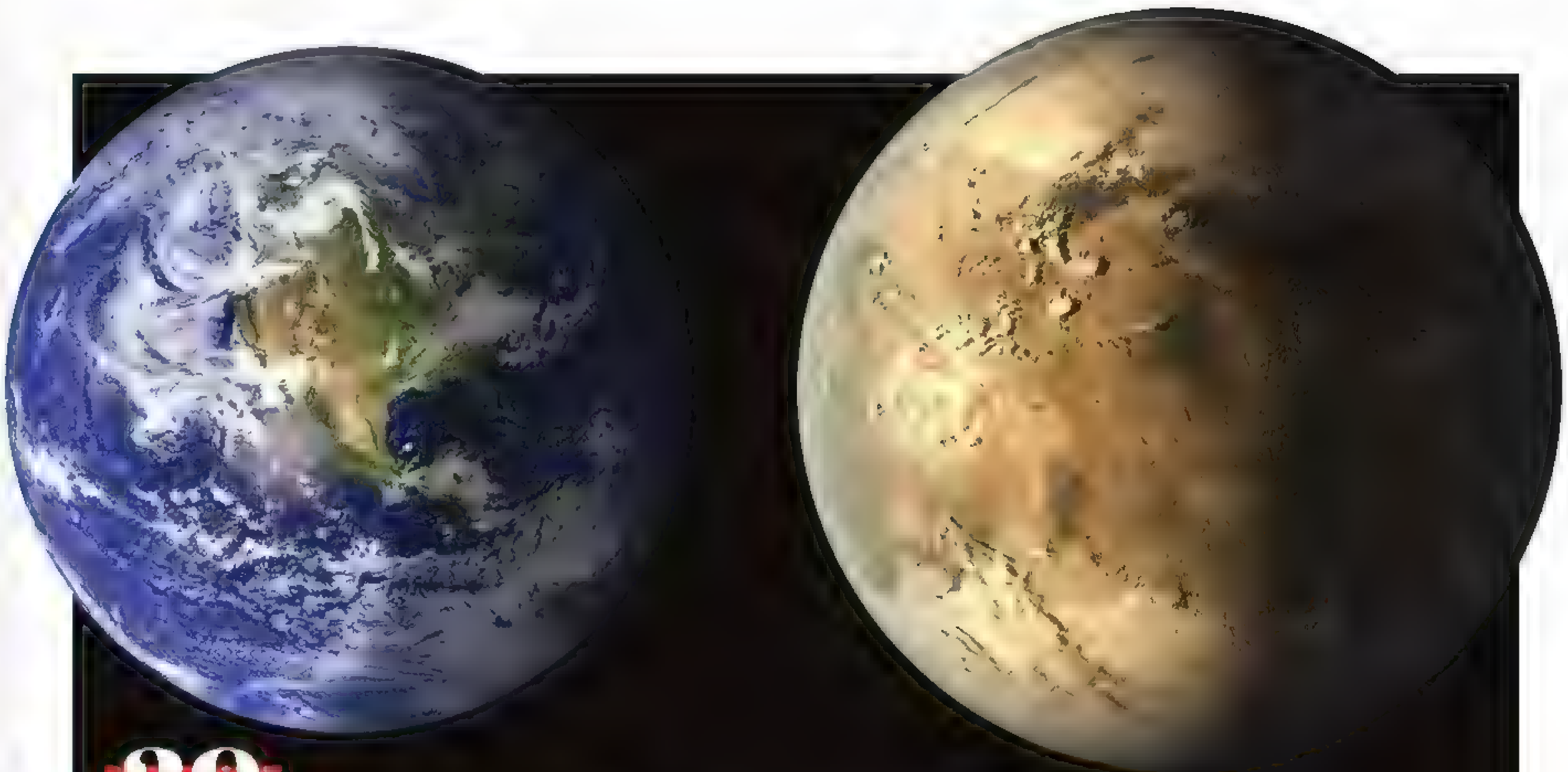
N The Parker Solar Probe came within 10.4 million kilometres (6.5 million miles) of the Sun's surface and became the first spacecraft to 'touch the Sun' when it flew through the solar corona in April 2021.

40

FASTER AND FASTER

By observing the redshift of distant supernovae in the late 1990s, two teams of astronomers discovered that not only is the universe expanding, it's doing so at an accelerating rate. "This wasn't expected because if all types of matter and energy in the universe were attractive, it would stop its expansion, recollapse at some point and end up in a 'Big Crunch' – a stage opposed to the initial Big Bang," Garcia says. "The accelerated expansion of our universe means there must be a missing ingredient in the total budget that overcomes gravity's attractive force due to 'negative' pressure." Dark energy was introduced at this time as a placeholder for whatever is expanding the fabric of space-time.





39

THERE IS NO EARTH 2.0

N Humanity is constantly discovering worlds that resemble ours outside the Solar System, many of which dwell in the habitable zone of their stars. Yet as our planet becomes more inhospitable and more turbulent due to the effects of climate change, it would be wrong to look at these worlds as alternatives for humanity to settle in the near future. That's because of the sheer magnitude of the distance between our planet and these worlds, which makes exoplanet colonies pure science fiction at the moment. As an example, consider the closest star system to the Solar System, Proxima Centauri, four light years away, and imagine there's an Earth-analogue planet around that star. The fastest human-carrying spacecraft is the Apollo 10 spacecraft, which raced through space at a top speed of 39,897 kilometres (24,791 miles) per hour – around 16 times as fast as the top speed of a F-16 jet fighter. Even travelling constantly at this top speed and assuming no diversions, it would have taken Apollo 10 roughly 114,000 years to reach the Proxima Centauri planetary system. Until the invention of near-light-speed travel or suspended animation, Earth is the only planet we've got… we must protect it.

> "WASP-76 b is an extraordinary discovery because of the sheer violence of this exoplanet"

38

THE BOILING EXOPLANET WHERE IT RAINS IRON: WASP-76 B

Discovered in 2013 as it crossed the face of its parent star, WASP-76 b wasn't the first exoplanet found, nor was it the first hot Jupiter, so what makes it a discovery fit for this list? WASP-76 b is an extraordinary discovery because of the sheer violence of this exoplanet, which makes our gas giants look a bit tame. Orbiting its star at a distance of just 0.033 times the distance between Earth and the Sun, WASP-76 b completes an orbit in just 1.8 Earth days. The planet, which is 1.83 times the width of Jupiter and 0.92 times the mass of the Solar System's gas giant, is tidally locked. This means that one side of the planet permanently faces its parent star, while one side perpetually faces space. This sends the temperature of the 'dayside' facing the star soaring to 2,400 degrees Celsius (4,350 degrees Fahrenheit), while the nightside, facing space, is relatively cooler at 1,500 degrees Celsius (2,730 degrees Fahrenheit). Temperatures at the dayside are so hot that iron is vaporised; it's then blown across to the nightside by powerful winds, where it cools and falls as iron rain.

37

OUR PLACE IN SPACE

Where in our vast galaxy is our home around the Sun located? In 1785, William Herschel performed counts of stars in the Milky Way and determined where Earth and the Solar System are located in our galaxy. But Herschel incorrectly placed the Solar System close to the heart of the Milky Way. As observations of the stars have proven him wrong, astronomers have shifted our position to 26,000 light years from the galactic centre, sitting perched at the inner edge of the Orion arm.

36

MISSING TYPE OF EXOPLANET

As they discover more exoplanets, astronomers discover a curious absence of Neptune-sized worlds close to their stars, terming this the 'hot Neptunian desert'.

35

DARK STARS

In 1783, John Michell suggested the existence of stars so dense that not even light could escape them. In 1796, Pierre-Simon Laplace suggested a similar idea, terming them 'dark stars'.

34

DIFFERENT TYPES OF SUPERNOVAE

The light spectrum coming from different supernovae shows these events have different origins, including Type Ia coming from the explosion of feeding white dwarfs.

33

HOW TO MAKE A TELESCOPE

In 1608, spectacle makers in the Netherlands, Hans Lippershey and Zacharias Janssen, and Dutch instrument-maker Jacob Metius, created the very first telescopes.

32

RED AND BLUESHIFT

The discovery that Doppler shift applied to the wavelength and frequency of light was crucial for the discovery that the universe is expanding and for modelling the motion of stars.

31

THE FINITE SPEED OF LIGHT

Astronomer Ole Rømer proposed in 1676 that light has a finite speed in a vacuum, eventually determined to be 1,080 million kilometres (671 million miles) per hour.

30
THE UNIVERSE ISN'T STATIC
Realising that the universe isn't static thanks to Edwin Hubble in 1929, Einstein removed the cosmological constant from his equations.

29
AN EXPANDING UNIVERSE
Cosmologists reintroduced the cosmological constant to account for the accelerating expansion of the universe and to describe the energy density of empty space.

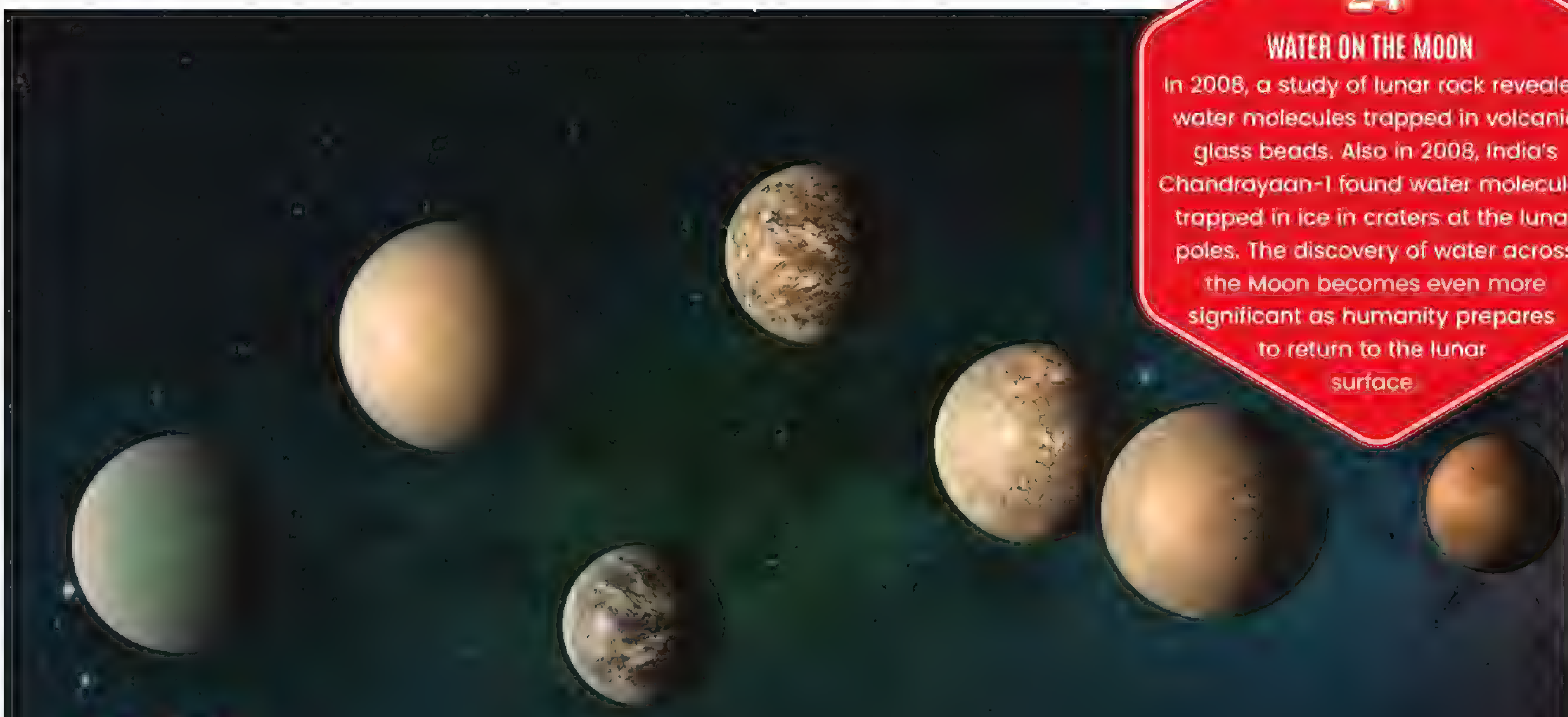
28
COSMIC RAYS
During a series of balloon flights from 1911 to 1912, Austrian physicist Victor Hess detected charged particles entering Earth's atmosphere from space, eventually ruling out the Sun as a source.

27
GAMMA-RAY BURSTS
On 2 July 1967, Vela 4A made the first measurement of a gamma-ray burst – powerful blasts of high-energy radiation that come from the birth of black holes and violent cosmic events.

26
THE SPEED LIMIT OF THE UNIVERSE
In 1905, Einstein developed special relativity, setting the speed of light in a vacuum, or 'c', as a cosmic speed limit that no object with mass can exceed.

25
RETHINKING SPACE AND TIME
In 1908, Hermann Minkowski suggested the three dimensions of space are united with the fourth dimension of time, forming a four-dimensional entity called space-time.

24
WATER ON THE MOON
In 2008, a study of lunar rock revealed water molecules trapped in volcanic glass beads. Also in 2008, India's Chandrayaan-1 found water molecules trapped in ice in craters at the lunar poles. The discovery of water across the Moon becomes even more significant as humanity prepares to return to the lunar surface.



23
SEVEN EARTH-LIKE WORLDS

The TRAPPIST-1 system is a planetary collection of seven planets orbiting a cool red dwarf star, located around 40 light years from Earth. Its discovery earns its place on this list because all of these exoplanets seem to have rocky compositions and are around the same size as Earth. Even more excitingly, three of these worlds orbit their star in the so-called habitable zone – the region around a star neither too hot nor too cold for a planet to host liquid water. The first two planets of the TRAPPIST-1 system were discovered in 2016, with the remaining five following soon after.

The conditions these worlds exist in make them golden targets for searching for the conditions needed to support life, and even for biosignatures – chemical fingerprints in an exoplanet's atmosphere that may have been produced by the processes of life. The James Webb Space Telescope made a beeline for the planets of the TRAPPIST-1 system in its first year of operations, making observations of TRAPPIST-1 b, a super-Earth with 1.4 times the mass and 1.1 times the width of our planet. Webb has measured the temperature of this planet using thermal emissions, which is the first time any light emitted by an exoplanet as cool and small as Earth has been measured.

22

PRECIOUS METALS

Neutron star collisions are determined as violent and turbulent sites in which gold, platinum and other elements heavier than lead are forged, with the detection of tellurium at such a site in 2023.

21

LUNAR CRATERS OBSERVED AND UNDERSTOOD

The origins of the 30,000-odd craters on the Moon would begin to become clearer in the 20th century, with meteorite bombardment confirmed as the cause.

20

A STAR OR A PLANET?

In 1995, Rafael Rebolo López, María Rosa Zapatero-Osorio and Eduardo Marín Guerrero de Escalante confirmed the existence of the first brown dwarf, Teide 1, in the Pleiades, 400 light years from Earth.

19

THE OLDEST GALAXIES

In its first release of data, Webb spotted galaxies which date back as far as 13.3 billion years, which means we are seeing them as they were when the universe was just 500 million years old.

18

THE COSMIC DISTANCE LADDER

Astronomers can measure cosmic distances thanks to the development of a series of scaling methods in a system called the cosmic distance ladder. Each 'rung' is calibrated using the prior rung.

17

ELECTROMAGNETIC SPECTRUM

It was the combined effort of scientists including Johann Wilhelm Ritter, Heinrich Hertz and William Herschel in piecing together the spectrum, including radio, X-ray, infrared, visible, gamma and microwave.

16

THE MILKY WAY IS NOT THE ONLY GALAXY

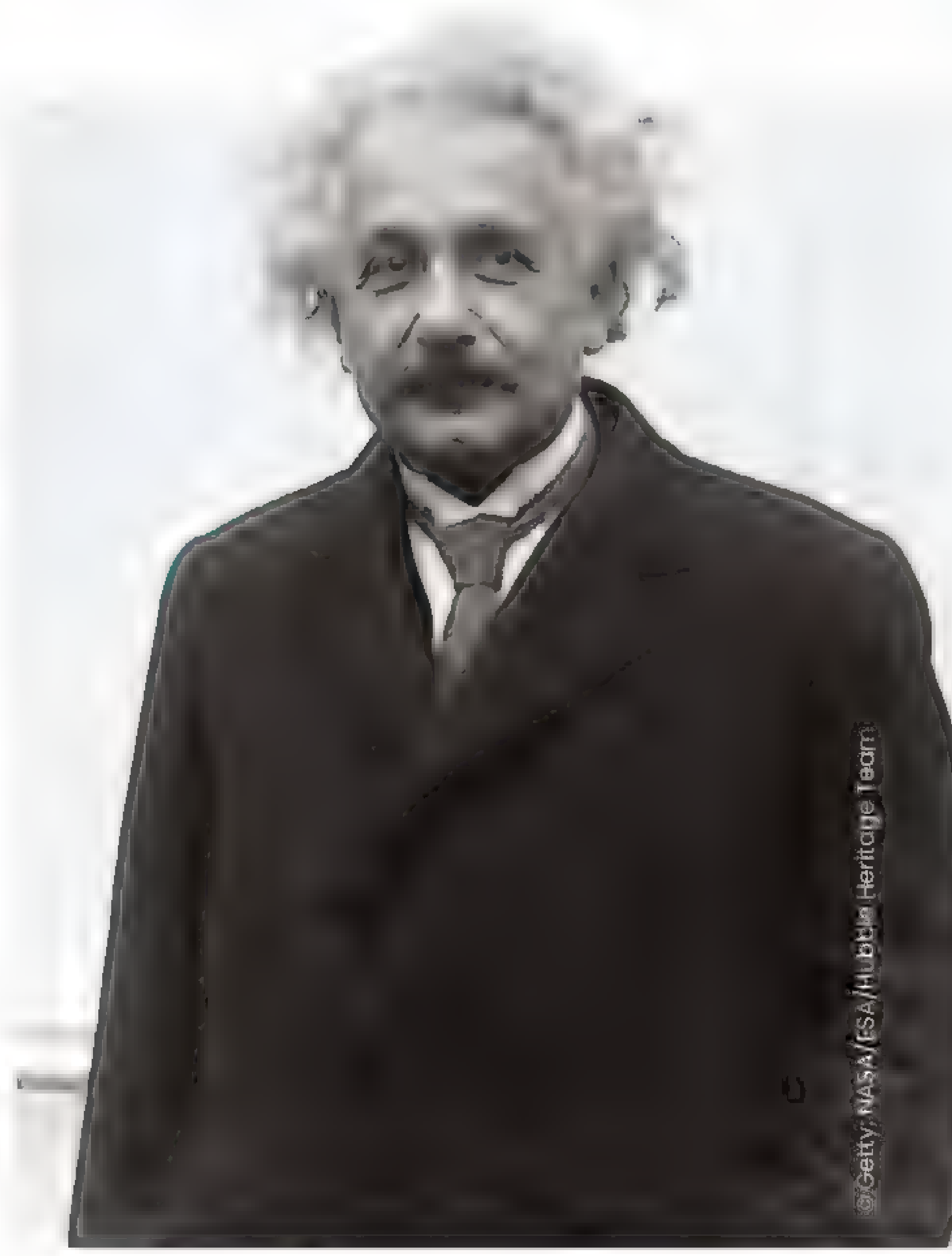
In 1923, Edwin Hubble discovered conclusively that there are galaxies outside of the Milky Way. As strange as it sounds, the question of whether other galaxies exist had been hotly debated prior to this. Hubble focused on Andromeda, a fuzzy spiral in the sky that many astronomers believed was located within the Milky Way itself and was a nebula of gas and dust – a stellar nursery where stars are born. Hubble disputed this, with he and other scientists perplexed by some odd features of Andromeda, such as the large number of supernovae within it and the relative faintness of these cosmic explosions.

Along with Heber Curtis of Lick Observatory, Hubble proposed that Andromeda was an 'island universe', a system of stars all of its own. Hubble confirmed this by measuring the distance to V1 – a variable star labelled the most important star in the history of cosmology – showing that Andromeda was definitely a galaxy and proving the existence of galaxies outside the Milky Way.

15

GENERAL RELATIVITY

Black holes, gravitational waves, gravitational lensing and neutron stars all owe their origins to general relativity. What this revolutionary idea suggested was that rather than being a force, gravity arises from a curvature of the very fabric of space and time caused by the presence of mass. The analogy for this is a stretched rubber sheet with balls of increasing mass placed on it. The greater the mass, the more extreme the dent. Stars create more curvature than planets, and black holes create more curvature than stars. The more extreme the curvature, the stronger the gravity in this region of space, informing matter how it should move around it. This explained the orbit of the planets and more.



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14

SEEING THE COSMIC GIANT AT THE HEART OF THE MILKY WAY

The second supermassive black hole that was imaged by humanity was the supermassive black hole at the centre of our home galaxy. In May 2022, the EHT Collaboration revealed to the world an image of Sagittarius A* (Sgr A*), the supermassive black hole that lurks at the heart of the Milky Way, around 26,000 light years from Earth. Despite the fact that Sgr A* is so much closer to our planet, the reason it wasn't the first black hole imaged is the massive size disparity between it and the black hole at the heart of Messier 87. Sgr A* is relatively small at 4.5 million times the mass of our star. Sgr A* is also far less wide than this more distant black hole, but the material around it still whips around it at near-light speeds. As a result, gas around Sgr A* completes an orbit over a period that is much quicker than the observing time of the EHT, making it more difficult to resolve and produce an image.

13

EXOPLANET AROUND A SUN-LIKE STAR

In 1995, 51 Pegasi b was discovered orbiting a Sun-like star by astronomers Michel Mayor and Didier Queloz. 51 Pegasi b is a hot Jupiter, a categorisation given to planets with sizes and masses comparable to that of Jupiter that orbit their parent star at incredibly close proximities, resulting in blisteringly hot surface temperatures and planets unlike anything found in the Solar System. At a distance equivalent to around 0.0527 times the distance between Earth and the Sun, 51 Pegasi b completes an orbit of its parent star in just 4.2 Earth days. The exoplanet has a mass 0.46 times that of Jupiter but is 1.27 times the width of the Solar System's gas giant.

12

A PLANET NO MORE

Pluto's demotion was because it met all but one criteria for a planet. It orbits the Sun and has the mass needed to assume a near-round shape, but it hasn't cleared out other bodies from its region of space.

11

GALILEAN MOONS

In January 1610, Galileo discovered the large moons of Jupiter, now known as Galilean moons: Io, Europa, Ganymede and Callisto. Galileo determined these were bodies orbiting Jupiter and not distant stars.

10

BIG STARS STICK TOGETHER

The more massive a star is, the more likely it is to be found with one or two companions in a multi-star system. Currently, 75 per cent of massive stars in the Milky Way are believed to have a binary companion.

9

THE MID-LIFE CRISIS OF THE SUN

During the 20th century, our star was aged at 4.6 billion years. It's halfway through the hydrogen fuel at its heart, which via nuclear fusion transforms into helium. Our star will begin to die in around 5 billion years.

8

THE ORCHESTRA OF THE COSMOS

In 2023, the North American Nanohertz Observatory for Gravitational Waves found complexity in the universe's symphony, detecting low-frequency gravitational waves for the first time.

7

THE UNIVERSE DOESN'T REVOLVE AROUND YOU

In 1543, Nicolaus Copernicus put forward the then-radical theory that Earth revolved around the Sun, and not vice versa. It would take over 100 years for this to be accepted.

6

ENERGY AND MASS

ESA Special relativity includes the most famous equation in history – the relationship between energy and mass, $E=mc^2$, which tells us that the energy (E) released when mass (m) is converted to energy is equivalent to that mass times the speed of light squared (c^2). The energy-matter equivalence also showed how stars create energy, vital for living things.

5

LIGHT TAKES A TURN

SU Due to the curvature of space-time, when light passes an object of huge mass, its path is curved. In an effect called gravitational lensing, this curving can amplify background light or make a single object appear at several places in the same image. This is used today by astronomers in observing early galaxies, ordinarily too distant and too faint to see.

4

INTERMEDIATE-MASS BLACK HOLES

CU In November 2004, astronomers discovered GCIRS 13E, a cluster of stars near the heart of the Milky Way that's believed to harbour an intermediate-mass black hole. In 2020, Australian astronomers witnessed what they believed was the birth of one of these middle-mass black holes, with a mass around 150 times that of the Sun.

3

A JUMBO DISCOVERY

N In October 2023, scientists revealed a curious discovery in the Orion Nebula: around 400 free-floating bodies. With planetary masses, the objects are theorised to have formed like stars, not like planets. The astronomers who discovered these objects using the James Webb Space Telescope have named them Jupiter-Mass Binary Objects, or JuMBOs.

N

2

HITTING OUT AT ASTEROIDS

In September 2022, NASA discovered what happens when you smack an asteroid really hard. The Double Asteroid Redirection Test (DART) was launched on 24 November 2021 and reached its target binary asteroid system, Didymos, the following September. When it arrived, the kinetic impactor slammed into the smaller of these two asteroids, Dimorphos, changing its orbital period.

1

BIRTH OF THE BIG BANG

UNC In 1931, Georges Lemaître, a Belgian cosmologist and priest, introduced the first formulation of the Big Bang theory – the concept that the universe began as an infinitesimally small point of dense energy that rapidly expanded. It was a radical departure from the 'steady state' theories of the universe that were commonly accepted in the 1930s. This discovery also meant that the universe wasn't eternal; time had a beginning, with a cosmic clock that started at that initial moment of rapid expansion around 13.8 billion years ago.

"We know the universe is expanding, and there are a plethora of different observations that validate this idea. If we look back to the past and reverse the equations that define the evolution of the space-time continuum, we are led to discover that the universe was smaller and denser in its early stages," says Garcia. "Therefore, there would have been a point in time when the universe was incredibly small – a singularity where our laws of physics stopped applying. This event, called the Hot Big Bang, defines the beginning of time in our universe." Our models of the universe and its evolution stretch back to this initial moment, showing that everything we see today came from the most infinitesimal of beginnings.

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